Stein,

This document describes a risk-based assessment that was performed as part of a planning study. The purpose of the study was to provide input to the selection of design basis events that would result in structures whose reliability is such that the chance of catastrophic dam failure is sufficiently low (i.e., dam failure risks did not pose an unacceptable risk to the local population). In addition, the study also provided input to a process for selecting future dam sites using performance goal concepts to develop proposed design basis events. In this case the performance goal for dams was defined in terms of an unacceptable frequency of failure (uncontrolled release of the reservoir).

Marty

Final Draft

San Diego County Water Authority Emergency Storage Project

Safety Goal Evaluation of Alternative System Designs

Prepared for
GEI Consultants, Inc.
Carlsbad, California

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1. INTRODUCTION

1.1 Overview

As part of a planning study, the San Diego County Water Authority (SDCWA) is considering alternative designs for an Emergency Storage Project (ESP). This document presents the results of a study in which a risk-based safety goal (SG) for dams proposed as part of alternative ESP designs is recommended. This study was performed under a subcontract to GEI Consultants, Inc. of Carlsbad, California.

To support the ESP planning study an evaluation was conducted in which a SG for the performance of dams was recommended. The SG establishes an upper bound on the mean frequency of dam failure. Given a SG, the study focuses on the characteristics that must be provided in the design of a dam such that there is a reasonable assurance that SG is satisfied.

At the time this study was conducted the project was in a conceptual design stage. As such detailed engineering analyses were not performed and quantitative estimates of factors of safety were not known. The objectives of this study and the scope of the evaluations are discussed in the following subsections.

1.2 Objectives

There are two primary objectives of this study. The first is to recommend a SG for dams that are considered as part of alternative ESP designs. A SG has two aspects to it. First, it establishes a reliability level for the performance of the dam. Secondly, it establishes a performance level that must be satisfied. The SG is a quantitative criterion for the likelihood that unsatisfactory performance of a dam will occur. The performance criterion is specified in terms of dam failure. The second objective is to provide guidance with respect to the characteristics that should be provided by the design of dams that are considered.

1.3 Scope of the Risk-Based Assessment

The objectives of this study are different from the objects of a conventional risk assessment that would be performed for an existing facility or one whose design is fully defined. In a conventional risk assessment for a dam the objective is to answer the question; What is the frequency of dam failure (given a specific site and design)? This is not the case in this study. Here, the following question is addressed; What should the design and construction characteristics of a dam be in order to achieve a certain degree of reliability (e.g., satisfy a SG)?

A conventional risk assessment can be characterized as a forward analysis in which an existing dam is evaluated and its reliability determined. Here, a top-down or deductive approach is used in which the reliability of a dam is known (actually specified) beforehand and using "backward logic" the characteristics of the design are determined In a top-down approach the evaluation focuses on the final result or top event of interest, in this case the frequency of dam failure. It then proceeds to evaluate a dam in terms of its more global characteristics or factors that influence its ability to resist applied loads. Depending on the information available, the analysis can proceed down to the level of detail required.

A first step in this study is the selection of a SG for the performance of dams. The SG is selected on the basis of a review of existing standards for other critical facilities. Once an overall SG is defined, it is proportioned to define a safety goal for individual modes of dam failure (e.g., seismic, hydrologic).

Given a SG, a risk evaluation is performed to identify the critical characteristics that must be provided by a dam design in order to satisfy the goal. To accomplish this, simplified risk models are used to model the performance of a dam. The models are constructed to represent the primary attributes of a dam's design, and/or factors that influence its reliability. The risk model is based on the conceptual dam designs and hazard information available at the time this study was initiated.

A key difference between the objectives of this study and a conventional risk assessment is the fact that a frequency of failure for a dam is not calculated as a product of the analysis. As noted, the SG (frequency of dam failure) is defined as a target level that must be satisfied. The SG is therefore used as the 'de facto' frequency of failure for each ESP dam considered. Having defined the frequency of failure, the structural characteristics or capacity that must be provided by the dam design is determined or "back calculated".

Each alternative ESP defines a system of dams, pipelines, pump stations, etc. that are designed to meet certain water supply requirements. Prior to the start of the study it was concluded that the risk to the public of a particular ESP design would be dominated by dam failure. As a consequence, the public health risk that might exist from failure of other components was not evaluated.

1.4 Report Organization

Section 2 describes the scope of the ESP risk assessment, defines key terms used in the report, lists the steps in the analysis and identifies the alternative ESP systems that are considered. Section 3 discusses the safety goal approach for the ESP. In addition, this section also references other applications where a safety goal approach is used in the context of the design for critical facilities. In Section 4 the risk assessment methodology and assumptions or conditions considered in this study are described. Section 5 presents the results of the seismic risk assessment for each dam considered in the alternative ESP systems. In Section 6 the assessment of hydrologic risk is presented, followed by Section 7 which addresses the risk due to other events. A summary of the risk evaluation and recommendations are presented in Section 8. References that are cited are provided in Section 9.

2. SCOPE OF THE ESP RISK-BASED ASSESSMENT

2.1 Overview

The starting point for this study is the selection of a SG that defines an acceptable level of performance for dams considered as part of an ESP system. As discussed in Section 3, the SG is defined in terms of an acceptable/limiting frequency of dam failure. Thus, at the start of an evaluation for a dam, the target frequency of failure is known. Using a risk model and a deductive or "backward" logic, the objective is to determine how a dam should be built, e.g., what the characteristics of the design should be to resist applied loads, that are consistent with the SG.

This section outlines the steps in the risk-based assessment. Subsection 2.2 provides an overview of the ESP risk assessment, including the definition of key terms. Subsection 2.3 lists the steps in the analysis and discusses the top-down approach that is used. Subsection 2.4 addresses the topic of uncertainties. Lastly, Subsection 2.5 identifies the alternative ESP systems that are considered.

2.2 Safety Goal Approach and Key Terms

2.2.1 Safety Goal Approach

From an engineering design and public policy perspective it is practical to establish a SG that provides a reasonable assurance that:

- a new dam does not add substantially to the prevailing public risk, and
- the reliability of new construction is better than the prevailing historic trend.

In this study the SG defines a limiting or target value for the frequency of dam failure. The SG corresponds to the total failure frequency. As a result the frequency of dam failure due to any and all modes of failure must, in sum, be less than or equal to the SG. Section 3 discusses the selection of the SG and addresses the approach used to provide assurance that the goal is met. Section 3 also provides examples where safety goals have been used for critical facilities.

2.2.2 Key Terms

This subsection defines a number of key terms that are used in this study.

Frequency of Failure - number of failure events expected to occur in a specified period of time. In this study the frequency of failure is estimated on a per year basis. (Note, strictly speaking the frequency of failure is different from the probability of failure.) However, for rare events the frequency of failure per year and the annual probability of failure are essentially the same

(numerically.)

Dam Failure - Failure of a dam in this study refers to the uncontrolled release of the reservoir. Analytically it is difficult to estimate the conditions under which a dam will fail and the load level that produces failure. As a result, a risk assessment will generally predict incipient failure, which typically is a level of performance (damage) beyond which it is difficult to accurately predict what will occur, but at the same time corresponds to a level beyond which the reliability of the structure is sufficiently low that it cannot be expected to retain the reservoir.

Factor of Safety - In this study the term factor of safety is used to denote the ratio between the estimated median (required)[1] capacity of a structure to the design basis. In general, it is equal to or greater than the factor of safety typically calculated in a design evaluation. The estimated median capacity corresponds to incipient failure.

2.3 Steps in the Risk Assessment

An objective of this assessment is to recommend a basis for design such that an acceptable level of risk is achieved. To do this, the following steps are taken:

1 A SG is selected that defines an acceptable, limiting value for the mean frequency of dam failure. A SG is selected that is realistically achievable for dams designed to current dam safety standards in California and at the same time represents an acceptable societal risk.

2. Considering there are a number of different ways in which dam failure could occur, the frequency of failure for all modes of failure must, in sum, be less than or equal to the SG. In order to satisfy the SG, the total frequency of dam failure is partitioned among the dominant modes of failure.

3. For the dominant modes of dam failure, a risk calculation is performed to estimate the structural or operational integrity that **must** be provided to meet the SG. This establishes a lower bound on the capacity of a dam that must be provided in the design.

4. In Step 3 the lower bound capacity of a dam is determined. In this step a simple, top-down risk model is used to model a dam's performance. The purpose of the risk model is to identify key features of the performance of a dam and to provide insights into the factors that affect its reliability.

5. Based on the risk model, insights into the design of a dam that must satisfy the SG are developed.

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[1]The term "required" refers to the capacity that must be provided to meet a safety goal. The term capacity is used in a general sense to refer to the capability of a dam to resist applied loads.

The risk evaluations are performed for each dam proposed as part of the alternative ESP system.

In the risk assessments that are conducted, a top-down approach is taken. The objective of the top-down analysis is to model the factors that provide a first order measure of the performance of a dam. In this way the primary events that are required to cause dam failure are modeled. In comparison, in a bottom-up approach a detailed model is constructed in which the performance of all components (e.g., structures, equipment items, and operator actions) are modeled to determine the combination of events that lead to failure.

2.4 Sources of Uncertainty - Estimates of Risk

The SG is defined in terms of the mean frequency of dam failure. To estimate the mean risk, the total variability in the evaluation of the frequency of failure must be quantified. There are two fundamentally different sources of variability that contribute to the ability to predict the occurrence (i.e., frequency) of an event (1-3). These sources of variability are referred to as randomness and uncertainty and are defined as follows:

Randomness - is the inherent or natural variability associated with an event or phenomena. Certain events, such as the result of tossing a coin, are inherently random. This type of variability is irreducible.

Uncertainty - refers to the inability to model the "real" world due to limited data, lack-of-knowledge or limitations of mathematical models to represent a system or event. The factors that contribute to uncertainty also lead to differences in professional judgement (e.g., differences between experts). Uncertainties, in principle, are reducible through the collection of more data, improved knowledge, etc.

The distinction between these sources of variability can be illustrated through an example. Consider the factors that contribute to the variability in predicting the occurrence of a magnitude 7.5 or greater earthquake on a fault. From experience we know that precise predictions of the location and time of earthquake occurrences cannot be made. Earthquakes occur randomly in nature. As an alternative to precise predictions of time and place, predictions are made in terms of the rate of occurrence, denoted $\lambda(m>7.5)$. The rate of occurrence quantifies the inherent randomness of earthquakes.

A fundamentally different source of variability is the uncertainty associated with estimating $\lambda(m>7.5)$. This variability may be the result of:

- limited seismic or paleoseismic data,
- data that is uncertain or incomplete, or
- differences between estimates of $\lambda(m>7.5)$ as determined by alternative stochastic models.

These sources of variability contribute to the uncertainty to estimate the rate of occurrence of earthquakes of magnitude 7.5 or greater.

A manifestation of the uncertainty in the individual parts of a risk assessment is the fact that the end products themselves are uncertain. For example, if the final result of the risk assessment is an estimate of the frequency of a seismically initiated dam failure, the uncertainties in the seismic hazard assessment and in the estimate of the seismic capacity of the dam lead to uncertainty in the estimated frequency of failure. An illustration of the uncertainty in the frequency of failure is shown in Figure 2-1. The mean frequency of failure, which is indicated on the figure, is skewed to higher frequencies (away from the central part of the probability density function). This is a result of the relatively large uncertainty and the range of the failure frequency results. Note, if there was no uncertainty in either the estimate of the seismic hazard or the response of a dam to ground motion, there would only be a single (e.g., point) estimate of the frequency of failure (i.e., no uncertainty).

Accounting for both types of variability is an important part of a risk assessment and is required to estimate the mean or expected value of the parameter of interest (1-3). In this study the randomness and uncertainty in the performance of dams is implicitly considered although a comprehensive uncertainty analysis was not performed.

2.5 Alternative ESP Designs

In this study four alternative ESP systems are considered. They are Alternative Systems 5, 10A, 18, and 25. For purposes of the risk assessment only the modified or new dams proposed in these alternatives are evaluated. Table 2-1 lists basic characteristics of each dam. Other components such as pipelines and pump stations are not considered. In addition, existing dams are not evaluated since the purpose of this effort is to focus on the added risk that would be attributed to new facilities.

Table 2-1

Characteristics of the Dams in the Alternative ESP Systems

Alternative System	Dam Name	Structure Type	Dam Height (ft)
5	San Vicente	Roller Compacted Concrete	301.5
10A	Moosa South	Concrete Faced Rockfill	341
18	San Vicente	Roller Compacted Concrete	283.5
25	Olivenhain	Roller Compacted Concrete	320
	San Vicente	Roller Compacted Concrete	272.5

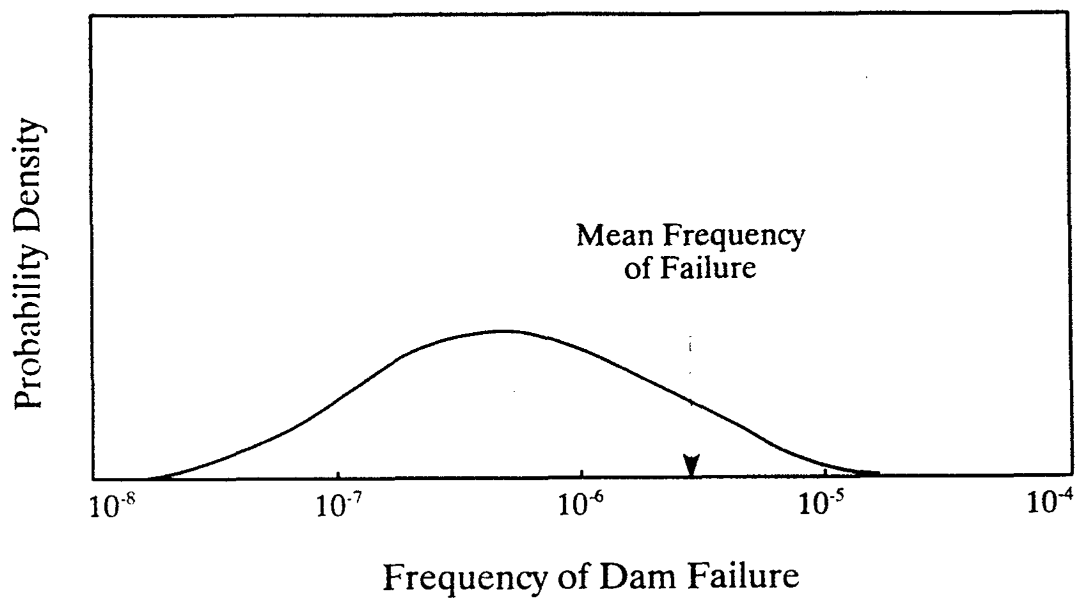

Figure 2-1 Illustration of a probability density function on the frequency of dam failure. The probability density function is a quantification of the uncertainty in the estimate of the frequency of failure.

3. SAFETY GOALS

3.1 Background

In this study a risk based-approach is used to provide insights to the design of dams considered as part of alternative ESP systems. The first step in this process is to define a SG for the performance of dams. A SG (sometimes referred to in engineering evaluations as performance goals) can be defined in different ways, depending on the measure(s) of safety that should be maximized. The selection of a SG can be based on the engineering performance of a structure or system, the risk to the public, the protection of a financial investment, or some combination. For example, in the case of dams, a SG can be specified in terms of:

1. The composite or total mean frequency of dam failure.

2. The risk to individuals resulting from a dam failure.

3. The societal risk defined by a frequency-loss curve that defines the mean frequency that levels of damage (economic loss) or fatalities would be exceeded per year.

The use of one or a combination of these SG formats depends on the application. In engineering applications a SG is typically selected that focuses on the performance of an individual structure or system. (Note, focusing on structure or system performance also implies certain limits on individual and societal risks.)

3.2 Selecting a Safety Goal

From an engineering design and public policy perspective it is practical to establish a SG for dams that provides a reasonable assurance that:

- a certain reliability is provided,

- a dam does not add substantially to the prevailing public risk, and

- the reliability of new construction is better than the prevailing historic trend.

The next subsection gives examples of applications where a SG approach has been used or proposed.

3.3 Examples of Safety Goal Applications

The use of risk assessment methods in engineering applications has increased significantly in the past two decades. In recent years the use of a risk-based approach to guide the design of critical structures has been applied in a number of areas. The focus of these assessments has been to utilize risk-based methods to establish consistent design and evaluation criteria. Examples where a SG approach or risk-based methods are used in the development of design standards include:

- Department of Energy design guidelines for natural phenomena (4),
- Department of Energy proposed standard for the design of the high level waste repository at Yucca Mountain, Nevada (5),
- Proposed Nuclear Regulatory Commission regulations for seismic siting of future commercial nuclear power plants (6),
- State of Washington guidelines for determining the design basis of dams (7),
- British Columbia Hydro risk management criteria (8), and
- recent Army Corps of Engineers policy statement that risk-based analysis should be used as part of the decision-making process when considering projects that are intended to reduce damage from flooding (9).

With the exception of the British Columbia Hydro (BC Hydro) risk management criteria and the Army Corps of engineers policy statement, each of the above applications defines a SG in terms of facility performance. BC Hydro has based their criteria on individual and societal risk constraints. The Corps of Engineers policy statement focuses on cost-benefit assessments.

U.S. Department of Energy - The Department of Energy (DOE) has developed design and evaluation guidelines for three natural phenomena hazards; seismic, wind and flood. The criteria were developed for use in the design of structures, systems and components (SSCs) (4). The basis of the DOE provisions is the establishment of performance goals for specified categories of SSCs. A performance category defines a group of structures, systems or components that are expected to behave in a similar manner and therefore must meet the same performance goal. A performance goal is defined in terms of an acceptable probability that behavior (response) limits for SSCs will be exceeded. Table 3-1 lists the DOE performance goals for each category.

For each performance category (and each natural phenomena) the DOE standard specifies the hazard annual probability of exceedance level that the SSC must be designed to. The design basis event is determined by entering the hazard curve for a site at the hazard annual exceedance probability. This is illustrated in Figure 3-1. In addition, the DOE standard also provides design provisions that must be followed. The design provisions are provided so that a SSC is designed and constructed with adequate strength and therefore has the necessary reliability (probability of not failing) for loads that equal or exceed the design basis. Taken together, the hazard annual probability of exceedance and the design provisions, SSCs designed according to the provisions of the DOE standard satisfy the performance goals (see Table 3-1).

U.S. Department of Energy High Level Waste Repository - The DOE is responsible for the design and construction of a High Level Waste Repository (HLWR) to store the nation's radioactive waste. As such they are developing seismic design criteria for HLWR facilities. The HLWR will consist of surface facilities whose design life will be approximately 100 years and an underground storage facility that must remain intact for a 1,000-year post closure period. DOE has proposed a procedure similar to the approach used in DOE Standard 1020-94 (4) to determine the seismic design basis for the HLWR facilities (5). The proposed standard establishes a performance goal for the HLWR that is similar to that for commercial nuclear power plants. An annual probability of unacceptable seismically induced performance of 10^{-5} has been proposed (5).

U.S. Nuclear Regulatory Commission - The USNRC has recently published proposed seismic siting regulations for future commercial nuclear power plants (6). The approach is similar to that in use by DOE in that seismic design loads are based on the results of a probabilistic seismic hazard assessment and the selection of the design basis ground motion at a specified probability level. For commercial nuclear power plants the proposed probability level is 10^{-5} per year. Although not stated in the proposed rule, this corresponds to an overall performance goal for core damage at future commercial nuclear power plants of approximately 10^{-6} per year.

Washington State Dam Safety Guidelines - The State of Washington has developed a procedure that is referred to as Consequence Dependent Design Levels and Balanced Protection (7). The procedure involves 8 design steps that are followed to determine the design basis events/loads for a dam. The design steps correspond to increasing consequence levels and correspondingly higher design requirements. The design steps have been calibrated to satisfy selected performance goals (7). For any step in the design procedure, the engineer is provided with a design level annual exceedance probability. Figure 3-2 shows the design level annual exceedance probabilities for each design step. The design level annual probability is then used to enter the hazard curve for a site (as shown in Fig. 3-1) to determine the design basis load.

The Washington procedure is applicable for determining the inflow design flood, assessing the seismic stability of embankments, design of outlet conduits, and reliability of critical electrical and mechanical systems.

British Columbia Hydro - BC Hydro is the electric utility for British Columbia, Canada and an owner of a number of large dams. As part of their in-house dam safety program, the utility has incorporated risk management methods. As a guide for decision-making, tolerable risk criteria are defined in terms of the individual and societal risk due to dam failure. In a number of respects the BC Hydro approach is similar in philosophy to that developed by the State of Washington in that it is consequence driven.

The BC Hydro criteria are displayed in Figure 3-3. The figure shows the criterion for the risk to an individual and the societal risk as defined by the frequency-consequence curve which defines the limit between safe and unsafe in terms of the frequency of the number of fatalities.

U.S. Army Corps of Engineers - Following the 1993 floods in the midwest the Corps of Engineers issued a circular that requires the use of risk-based analyses in the consideration of flood reduction projects. The risk assessments must be performed as part of the economic evaluations that are conducted to maximize the net benefits of flood reduction systems. In addition, as part of these evaluations the uncertainty in the flood evaluation and the impact of flooding must be considered.

3.4 ESP Safety Goal

Historically, estimates of the frequency of dam failure fall in the range of 10^{-4} to 10^{-5} failures per dam year (10). These estimates are generally based on the total population of dams or some large segment of the population (e.g., dams of a given type). Within the population of dams that comprise historic estimates, there is a wide range of engineering and construction practices that are represented. As a result there is a wide range in terms of the reliability of individual projects.

For dams proposed as part of alternative ESP systems, a SG is defined in terms of the mean annual frequency of dam failure. The SG is selected to achieve certain objectives. First, it serves as a guide to the design and construction of ESP dams to provide a reasonable assurance that the risks to the public from a failure are minimized. This suggests that the SG be set at a level below the prevailing risks to the public from other hazards (e.g., natural and man-made). A second objective is to select a SG that is at least consistent with safety goals that have been applied to comparable facilities (e.g., dams, nuclear power or other critical facilities). Finally, it is the objective of the SDWA to design the ESP to high technical standards, providing an efficient, safe facility. To satisfy these objectives, a SG of 10^{-6} per year, mean frequency of dam failure, is selected. This goal has the following attributes:

- Approximately two orders of magnitude less than the prevailing public health risk for individuals (11),
- At least one order of magnitude less than the historic rate of dam failure,
- Consistent with the performance goals set by BC Hydro and the State of Washington for dams that pose a high hazard.
- Consistent with the performance goals used by the Department of Energy for nuclear facilities that pose the highest hazard (Performance Category 4).

Note, in making these comparisons it should be kept in mind that the SG used in this assessment (i.e., the frequency of dam failure) is in fact a surrogate for a safety measure based on public health risk (e.g., the BC Hydro criteria displayed in Figure 3-3).

3.5 Meeting the Safety Goal

The total frequency of failure can be estimated as the sum of the failure frequencies for individual

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modes of dam failure. This is denoted:

$$\nu_f = \sum_i \nu_i \tag{3-1}$$

where ν_i is the frequency of dam failure due to failure mode i and the sum is carried out for all modes of failure. The key step in a risk assessment is to estimate the frequency of failure, ν_i, for each failure mode.

The SG for a dam can be met if it is partitioned such that each mode of failure is allotted a fraction of the overall goal. This concept can be represented in terms of a chart as illustrated in Figure 3-4 in which the 'pie' is comprised of individual slices. Each slice corresponds to the frequency of dam failure due to a particular event or failure mode (e.g., seismic event, foundation failure, etc.). The relative proportion of each slice defines the fraction contribution of the event to the total frequency of dam failure. The ability to meet the overall SG is assured if the goal for each mode of failure is met.

Note, the illustration suggests that the events (e.g., slices) that cause dam failure are mutually exclusive. In fact they are not, since certain events can occur simultaneously. For example, a large earthquake and a large inflow flood could, physically occur at the same time. From the perspective of modeling the occurrence of such rare events (e.g., events that lead to dam failure), it is reasonable to assume that the major contributors to dam failure are independent and that the likelihood of events that could jointly lead to failure is small in comparison to the total failure frequency. Using the example above, the frequency of the joint occurrence of a seismic event that leads to failure and simultaneously an inflow flood that also causes failure is approximately equal to the product of the individual event frequencies, which is small in comparison to the magnitude of either event by itself.

The overall SG can be defined in terms of the SG for individual failure modes. This is expressed by:

$$\nu_{SG} = \sum_i \nu_{SG,i} \tag{3-2}$$

or by

$$\nu_{SG} = \sum_i f_i \nu_{SG} \tag{3-3}$$

where f_i is the fraction allocation of the overall SG for an individual failure mode. The partitioning of the SG is discussed in the next section.

Table 3-1

U.S. Department of Energy Performance Goals

Performance Category	**Performance Goal Description**	**Performance Goal Annual Probability of Exceeding Acceptable Behavior Limits**
0	No Safety, Mission, or Cost Consideration	No requirements
1	Maintain Occupant Safety	$\sim 10^{-3}$ of the onset of damage to the extent that occupants are endangered
2	Occupant Safety, Continued Operation with Minimum Interruption	$\sim 5 \times 10^{-4}$ of damage to the extent that the component cannot perform its function
3	Occupant Safety, Continued Operation, Hazard Confinement	$\sim 10^{-4}$ of damage to the extent that the component cannot perform its function
4	Occupant Safety, Continued Operation, Confidence of Hazard Confinement	$\sim 10^{-5}$ of damage to the extent that the component cannot perform its function

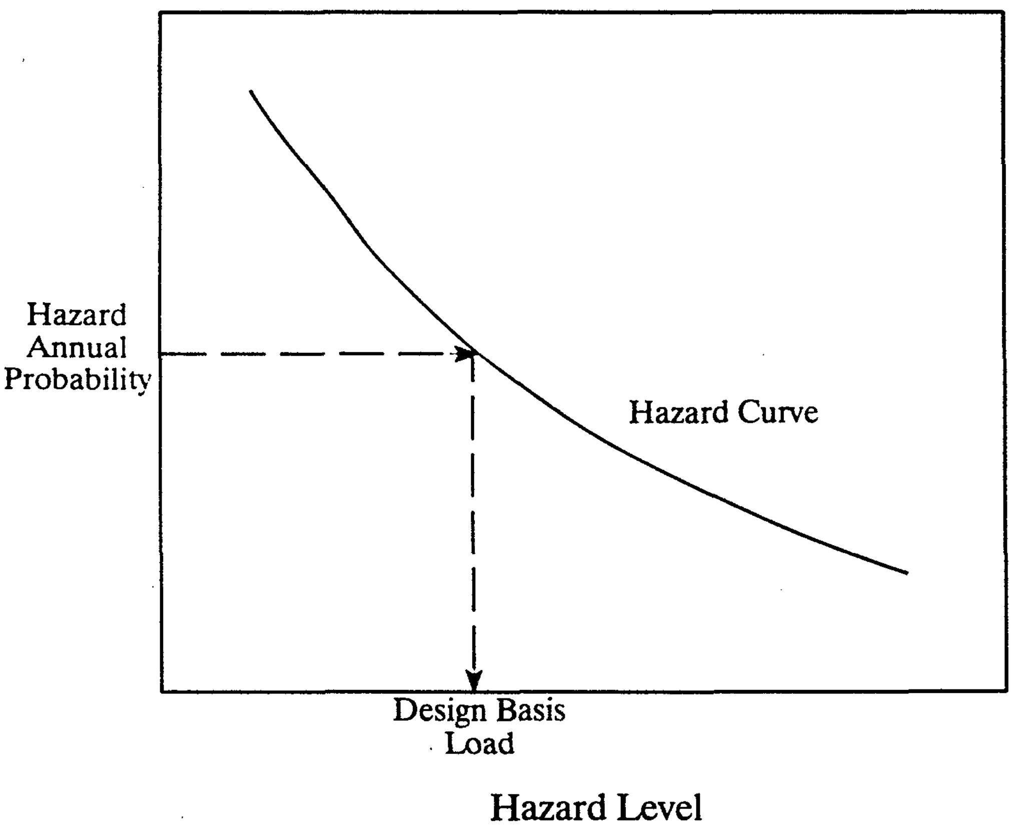


Figure 3-1 **Illustration of the determination of the design basis hazard corresponding to the hazard annual probability of exceedance.**

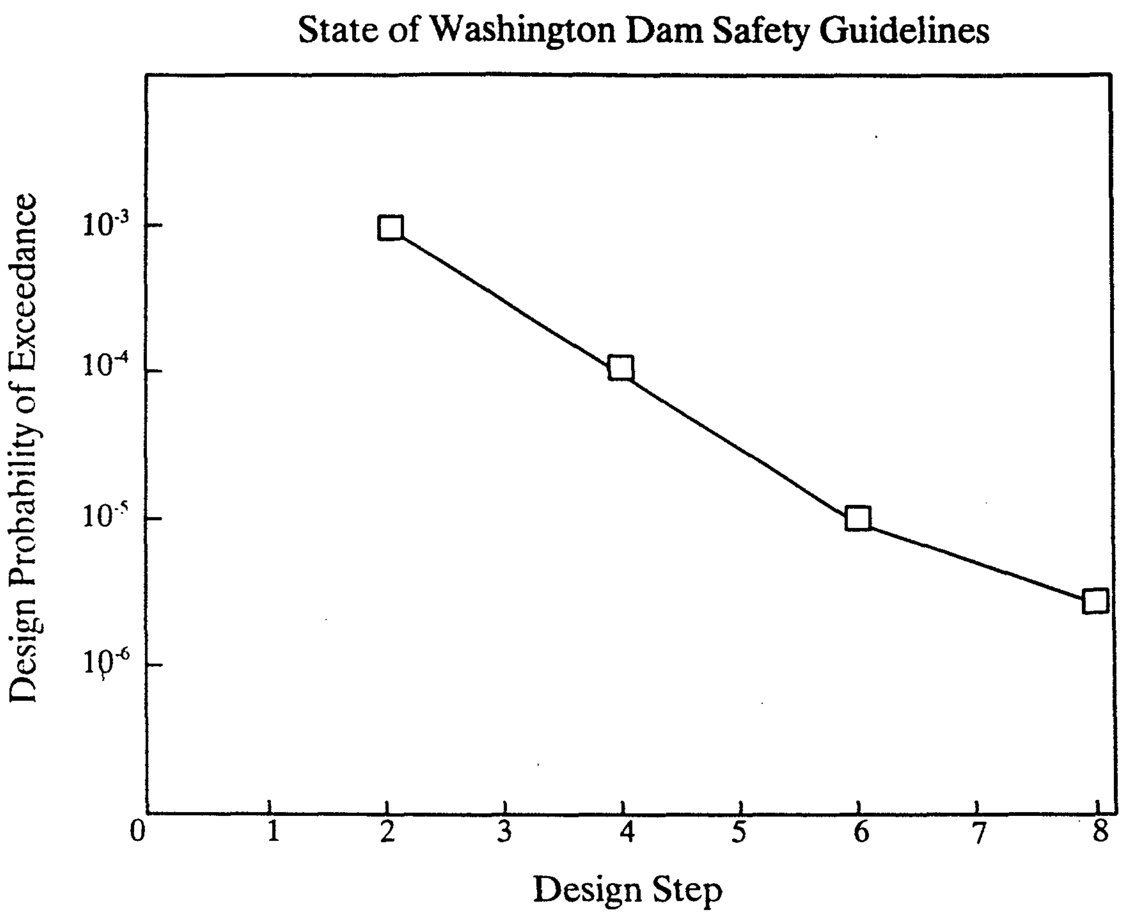


Figure 3-2 State of Washington design annual probabilities for each design step.

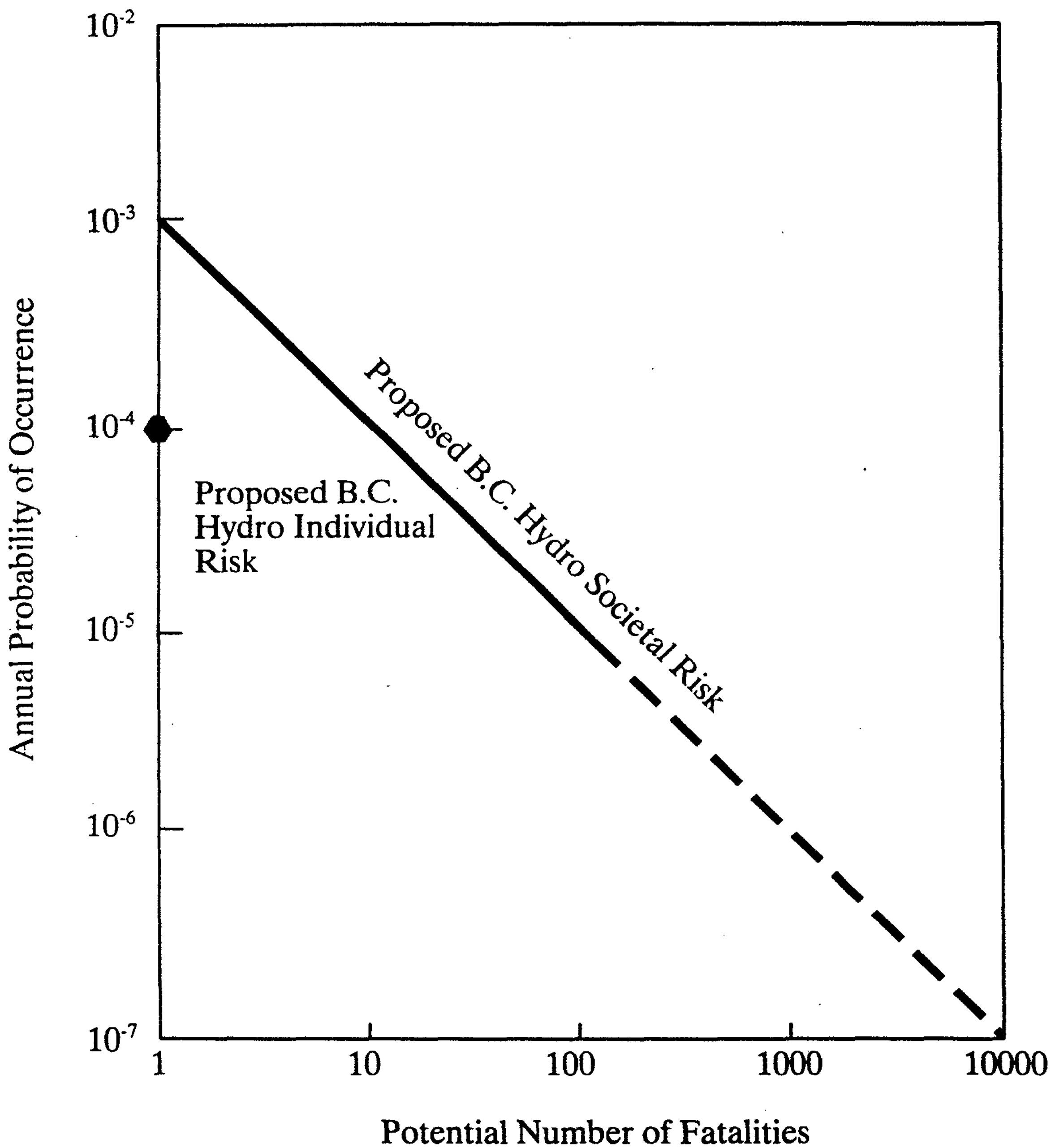


Figure 3-3 BC Hydro risk criteria.

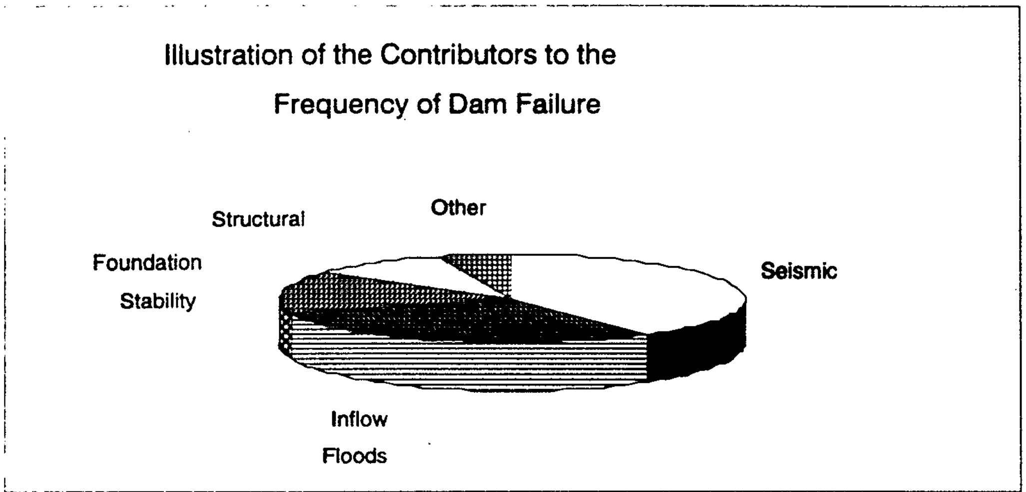


Figure 3-4 Illustration of the partitioning of the safety goal among different modes of dam failure.

4. RISK ASSESSMENT METHODOLOGY

4.1 Approach

This section outlines the approach taken to perform the risk evaluations in this study. For the dominant modes of dam failure, a SG is defined based on a partitioning of the overall SG that must be satisfied. Using a top-down approach, simple models are developed to determine the reliability that should be provided by the design for a dam.

4.2 Modes of Dam Failure

Possible causes or modes of dam failure include:

- seismically initiated failure that occurs as a result of ground shaking, fault offset, seiche, or landslide induced waves in the reservoir,
- overtopping due to hydrologic events or large inflow floods (such as due to an upstream dam failure),
- wind-waves that impact and possible overtop the dam,
- internal erosion/piping of earth or rockfill embankments,
- static instability (overturning or sliding of gravity dams, embankment slumps/slides in earth dams),
- landslide induced waves that overtop the dam,
- design or construction errors that produce a vulnerability in the dam, or
- operator actions that initiate an accident or contribute to events that lead to a dam failure.

The likelihood of failure for each failure mode will differ, depending on the design of a dam, the environmental conditions, quality of construction, etc.

For new dam construction it is assumed that the dominant contributors to dam failure will be seismic and hydrologic events. Seismic events are assumed to be the single largest contributor to dam failure. Individually, all other modes of failure are considered to be small contributors to the total frequency of dam failure. Based on these assumptions three primary modes of dam failure are explicitly considered; Seismic, Hydrologic and all Others.

Based on this assumption, the SG is partitioned in terms of the dominant failure modes so that the following holds:

$$\nu_{SG} = \nu_{SG,S} + \nu_{SG,H} + \nu_{SG,O} \qquad (4\text{-}1)$$

where $\nu_{SG,S}$ is the seismic safety goal. Similarly, the subscripts H and O denote the safety goals for hydrologic and other events, respectively.

To satisfy the SG, the risk of dam failure is partitioned among the three dominant modes of dam failure; seismic, hydrologic and all others. The partitioning of the SG is based on historic experience, engineering judgement, the site hazards and the need to develop a balanced design. From an historic perspective hydrologic events and geotechnical/geologic factors (e.g., foundation, dam stability) have been dominant contributors to past dam failures. Failures associated with foundation problems are, in many cases, related to inadequate site investigations. Experience with regard to the performance of dams during seismic events has been good, although the record is not as extensive as it is for other events (e.g., hydrologic). At the same time however, the alternative ESP dams are located in a seismically active region. Consequently, the seismic hazard (e.g., the likelihood of a dam experiencing strong ground motion during it's operating life) is high.

In distributing the risk of dam failure among the individual failure modes it is important to recognize that the distribution is made in the context of a design that satisfies the overall SG of 10^{-6}. In addition, as the fraction assigned to one failure mode or another is adjusted (higher or lower), there is a corresponding adjustment among the remaining failure modes. From a practical perspective, the design of a dam for a particular hazard/load (e.g., seismic) is not, in a strict sense, independent of the design for other loads. For example, if the seismic design of a dam must provide a particular factor of safety (in order to satisfy the SG), this will likely provide benefits in the reliability of the dam exposed to other loads (e.g., lateral loads generated by hydrologic events, static lateral loads).

Table 4-1 lists the fraction distribution of the overall SG among the different failure categories. The largest fraction for the risk of dam failure is assigned to seismic events. The basis for this is:

- the level of seismicity in the region,
- the higher level of uncertainty associated with evaluating the performance of dams during earthquakes, which is due in part to the limited experience (relative to other events) available.

By assigning a large fraction of the risk to seismic events, it is anticipated this will provide the designers with the greatest flexibility in the dam design to meet the overall SG. The remainder of the risk is distributed among the other failure modes. The distribution in Table 4-1 assumes that for many modes of failure, the likelihood of failure is reduced to levels that makes them, in effect, non-contributors.

To satisfy the SG, the risk of dam failure is partitioned among the three dominant modes of dam failure; seismic, hydrologic and all others. The partitioning of the SG is based on historic experience, engineering judgement, the site hazards and the need to develop a balanced design. From an historic perspective hydrologic events, geotechnical/geologic factors (e.g., foundation, dam stability) have been dominant contributors to past dam failures. Failures associated with foundation problems are, in many cases, related to inadequate site investigations. Experience with regard to the performance of dams during seismic events has been good, although the record is not as extensive as it is for other events (e.g., hydrologic). At the same time however, the alternative ESP dams are located in a seismically active region, in proximity to active faults. Consequently, the seismic hazard (e.g., the likelihood of a dam experiencing strong ground motion during it's operating life) is high.

In distributing the risk of dam failure among the individual failure modes it is important to recognize that the distribution is made in the context of a design that satisfies the overall SG of 10^{-6}. In addition, as the fraction assigned to one failure mode or another is adjusted (higher or lower), there is a corresponding adjustment among the remaining failure modes. From a practical perspective, the design of a dam for a particular hazard/load (e.g., seismic) is not, in a strict sense, independent of the design for other loads. For example, if the seismic design of a dam must provide a particular factor of safety (in order to satisfy the SG), this will likely provide benefits in the reliability of the dam exposed to other loads (e.g., lateral loads generated by hydrologic events, static lateral loads).

Table 4-1 lists the fraction distribution of the overall SG among the different failure categories. The largest fraction for the risk of dam failure is assigned to seismic events. The basis for this is:

- the level of seismicity in the region,
- the higher level of uncertainty associated with evaluating the performance of dams during earthquakes, which is due in part to the limited experience (relative to other events) available.

By assigning a large fraction of the risk to seismic events, it is anticipated this will provide the designers with the greatest flexibility in the dam design to meet the overall SG. The remainder of the risk is distributed among the other failure modes. The distribution in Table 4-1 assumes that for many modes of failure, that the likelihood of failure is reduced to levels that makes them, in effect non-contributors.

4.3 Steps In a Risk Assessment

For each failure mode that is explicitly evaluated, there is a SG (e.g., $\nu_{SG,i}$) that must be satisfied. To satisfy a SG, a dam design must be developed that provides adequate strength and safeguards against dam failure.

The first step in the risk evaluation is to determine the strength/capacity required to meet the SG. When the required capacity is determined a simple logic model is developed. The logic model is a top-down representation of the combination of events that could contribute to the failure of a dam. Event or logic tree techniques are used to develop the logic models. A logic tree can be used to model the progression of events as they would occur in time and to model dependencies between events. For each event that is modeled, the possible values/event states (failure or success) are defined by branches in the tree. Events considered in a logic tree are referred to as top events. A path through the event tree which involves a combination of event branches defines a logic tree sequence. For each top event, a probability is assigned to the event states (failure/success). The event state probabilities may be dependent on the state of events that proceed it in an event tree sequence. In this case, the event state probabilities are conditional. The probability that a particular sequence occurs is simply equal to the product of the event probabilities involved in the sequence. Figure 4-1 shows an example of a logic tree.

In this analysis the logic models are used to provide insights to the factors or events that impact the reliability of a dam. This objective is distinct from trying to "model" the performance of a particular dam in which a detailed analysis of the design is made, such as would be conducted in a "forward" risk assessment.

In quantifying the logic models, judgement is used to estimate the probability of each event state. The selection of event probabilities is guided by the following considerations:

- a need to determine the level of reliability required to meet the SG (e.g., how reliable must a particular part of the design process be),
- logical proportion/ranking of event probabilities (e.g., is one event more likely to occur than another), and
- engineering experience/judgement regarding the likelihood of an event.

The use of subjective assessments of event probabilities in risk assessments is common and often required, due to lack of quantitative data (14). In addition, since the focus of this risk assessment is to evaluate the relative importance of different factors or events, a detailed determination of event probabilities is not required.

4.4 Estimating the Required Capacity For External Loads

This section summarizes the procedure for estimating the capacity of a dam exposed to external loads (e.g., seismic, hydrologic). For purposes of this report, external loads on a dam are loads that are not imposed as a result of static gravity forces, but rather are dynamic and transient in nature. Static gravity forces include the lateral reservoir loads on a dam, uplift pressures, and seepage resulting from gravitational flow. Examples of external loads include the ground shaking resulting from a seismic event, the overtopping forces associated with a large inflow flood, and wind waves that impact the dam.

The frequency of dam failure due to an external load is determined according to:

$$\nu_f = \int \nu(x)\, P(f|x) dx \tag{4-1}$$

where,

ν_f = frequency of failure

$\nu(x)$ = frequency of occurrence of the load whose magnitude is x (e.g., a hazard curve for earthquake ground motion)

$P(f|x)$ = conditional probability of failure of the structure or system given the load level x; the fragility curve

The integration in equation 4-1 is performed over the full range of loading. Figure 4-2 shows the hazard-fragility curve relationship. The fragility curve for a structure (or a whole system) varies from low conditional probabilities of failure at low load levels to a conditional probability of failure of 1 (certain failure) at some high load level. For many civil type structures and systems, the fragility curve has an S-shape, characteristic of a complementary cumulative distribution function for a Lognormal or Normal distribution functions. The load level at which there is a 0.50 conditional probability of failure is referred to as the median capacity. The median is often referred to as the "best estimate" of the load required to cause failure. The conditional probability of failure varies as a function of load level due to the inherent variability (randomness) in material properties and the random signature of applied loads.

To estimate the mean frequency of failure as required in this assessment, the mean hazard curve and the mean fragility curve are used in equation 4-1. The mean hazard and mean fragility curves are determined by accounting for the uncertainty in their estimates.

For each external event that is explicitly considered in this analysis, the limiting frequency of failure is specified (e.g., the safety goal) and the hazard for the site is known (or assumed). Referring to equation 4-1, the task in this study is to determine the "required" fragility curve (e.g., minimum capacity) that must be provided by the design of a dam. The required fragility curve for a structure defines a lower bound on the loads that can cause failure. Alternatively, the required fragility curve can also be interpreted as defining the upper bound on the conditional probability of failure at each load level.

The required fragility curve is determined by trial and error. An initial fragility curve is assumed and integrated with the mean hazard curve for the site. If the calculated frequency of failure does not exactly equal the SG, the fragility curve is adjusted accordingly. This process is continued until the combination of the hazard and fragility curves exactly equals the SG.

The result of this process is a fragility curve for a dam that must be provided by the design. It defines a limiting lower bound that must be satisfied in order to meet the SG. By definition, if the "true" fragility for a dam is less than the required curve (e.g., shift the fragility curve to the left), the frequency of failure will exceed the SG. This interpretation of the required fragility curve is illustrated in Figure 4-3.

The required or limiting fragility curve for a dam is in fact a system level or composite fragility curve. When a dam is exposed to an external hazard (e.g., a large inflow flood or ground motion from a seismic event), different combinations of events can lead to failure. The number of scenarios and the events involved depends on the type of dam, how it is operated, the design of the dam, etc. These scenarios are often modeled through the use of event trees (also called logic trees) and fault trees. Fault trees are often used to model the events that can lead to failure of a particular structure or component.

Figure 4-4 shows an example of a fault tree used to model the seismic failure of a dam. The seismic failure is referred to as the top event. In the figure, failure of a dam due to an earthquake occurs if the dam fails in any one of the three possible failure modes; sliding at the foundation interface (FS), structural failure of the dam (SF), or overturning (OT). The fault tree illustrates that seismic failure occurs if the dam fails in any one of the three possible modes of failure.

The expression for the conditional probability of failure of the dam, (e.g., the system fragility curve), given a level of shaking a, is approximately equal to:

$$P(F|a) \approx P(F_{FS}|a) + P(F_{SF}|a) + P(F_{OT}|a) \qquad (4\text{-}2)$$

where:

$P(F_{FS}|a)$ = conditional probability of failure for sliding at the foundation interface given a level of shaking a

$P(F_{SF}|a)$ = conditional probability of structural failure given a level of shaking a

$P(F_{OT}|a)$ = conditional probability of overturning failure given a level of shaking a

This expression reflects the fact that the dam is a series system and failure results if any one mode of failure occurs.

In a top-down approach, the analysis focuses on the estimate of the total system conditional failure probability, $P(F|a)$, and the failure probability for the one or two modes of failure that are critical.

This study will define limiting values for $P(F|a)$ that must be satisfied by the design of a dam.

$P(F|a)$ is determined from a quantification of event trees and fault trees. It accounts for the multiple individual modes of dam failure and the combination of events that collectively could fail a dam. Figure 4-5 illustrates how individual failure mode fragility curves can combine to produce a total system level fragility curve. The system fragility curve is shifted to the left of the individual failure mode fragility curves. This shift denotes the fact that the system as a whole is weaker (is likely to fail at lower load levels) than any one failure mode. This is a consequence of the fact that there are three different ways/opportunities for failure to occur.

Table 4-1

Event Safety Goal Fractions

Event	Fraction of the SG
Seismic	0.90
Hydrologic	0.04
Static (all other events)	0.06

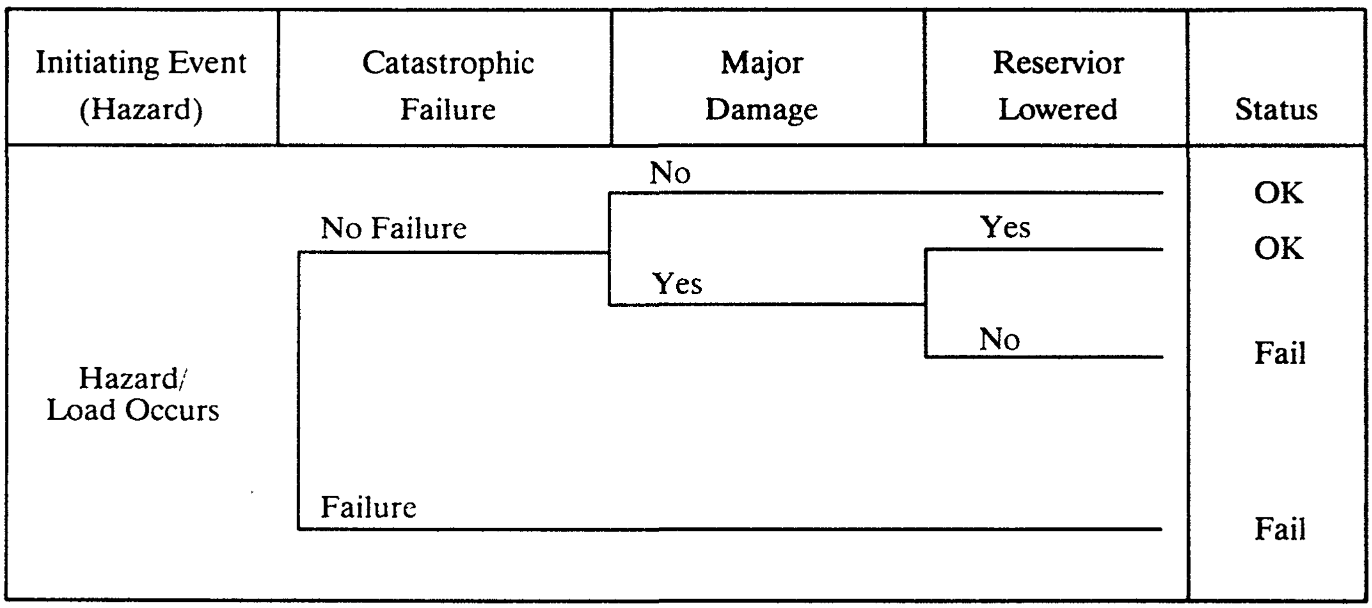


Figure 4-1 Illustration of an event tree.

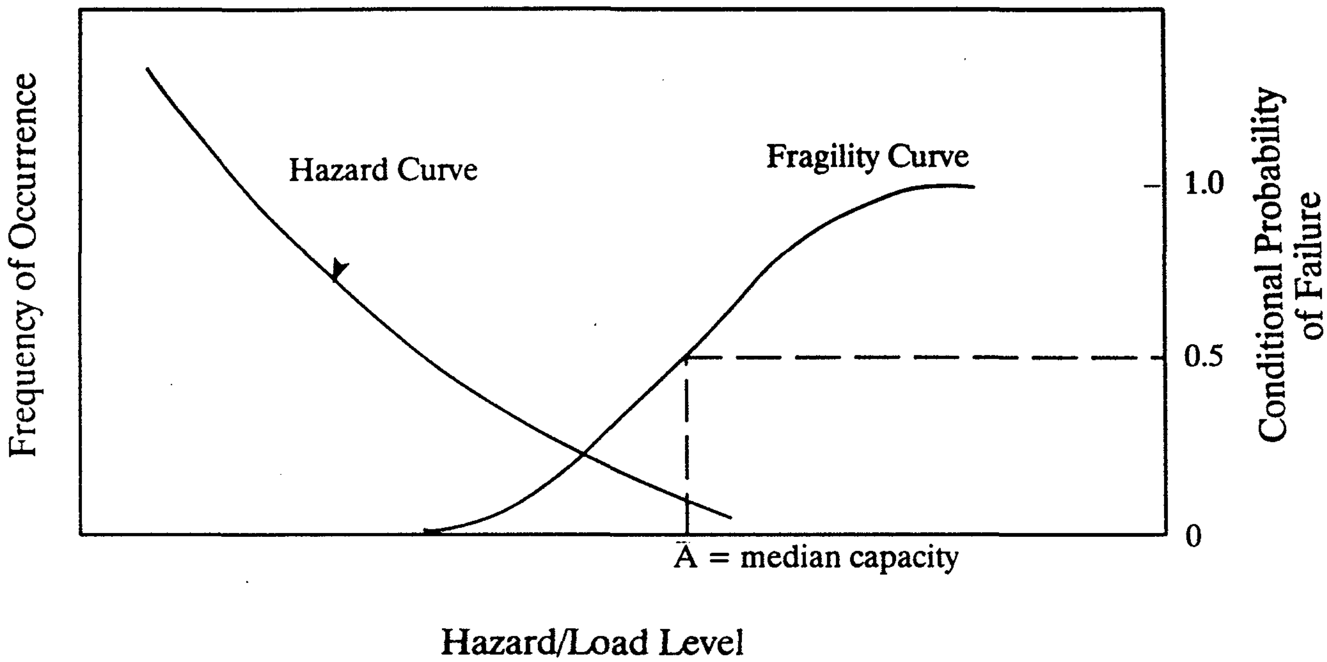


Figure 4-2 Illustration of the hazard-fragility integration process to estimate the frequency of failure.

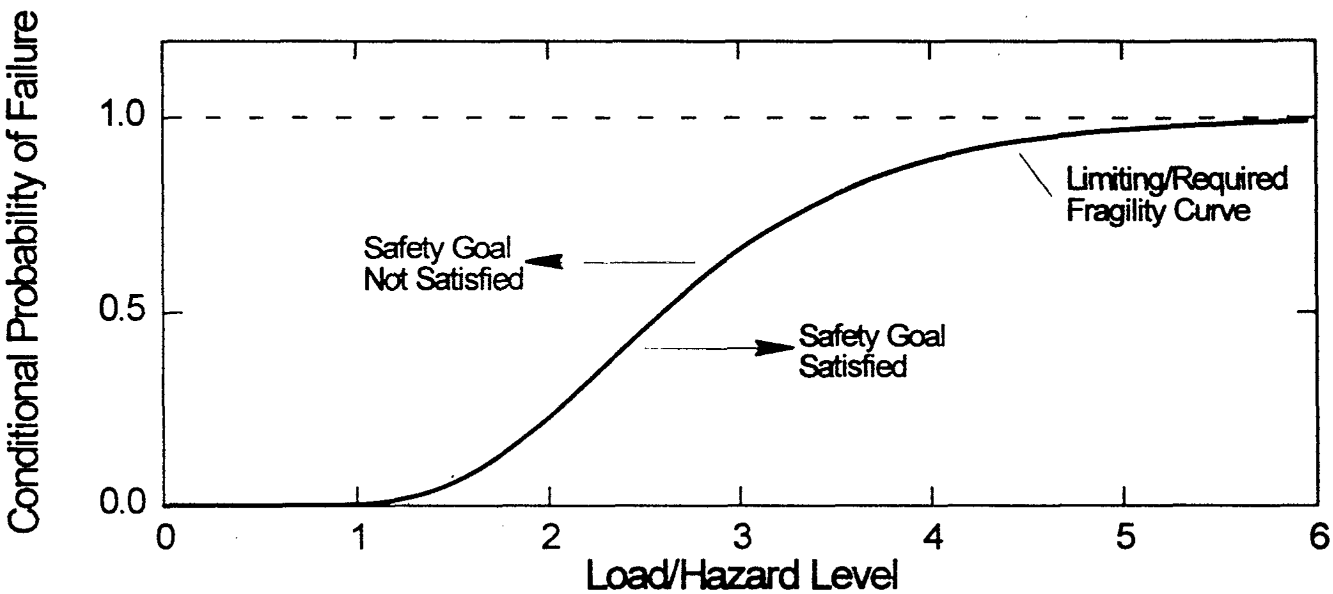
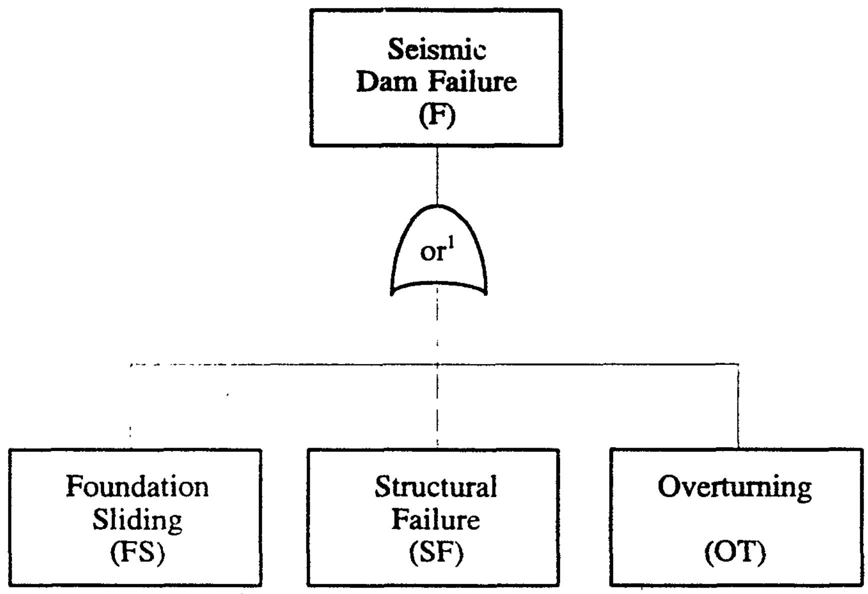


Figure 4-3 Illustration of the limiting/required fragility curve for a dam system.



[1]This symbol denotes that the top event (seismic dam failure) can occur if failure occurs due to any one of the following events: foundation sliding, or structural failure, or overturning

Figure 4-4 Illustration of a fault tree model for dam failure.

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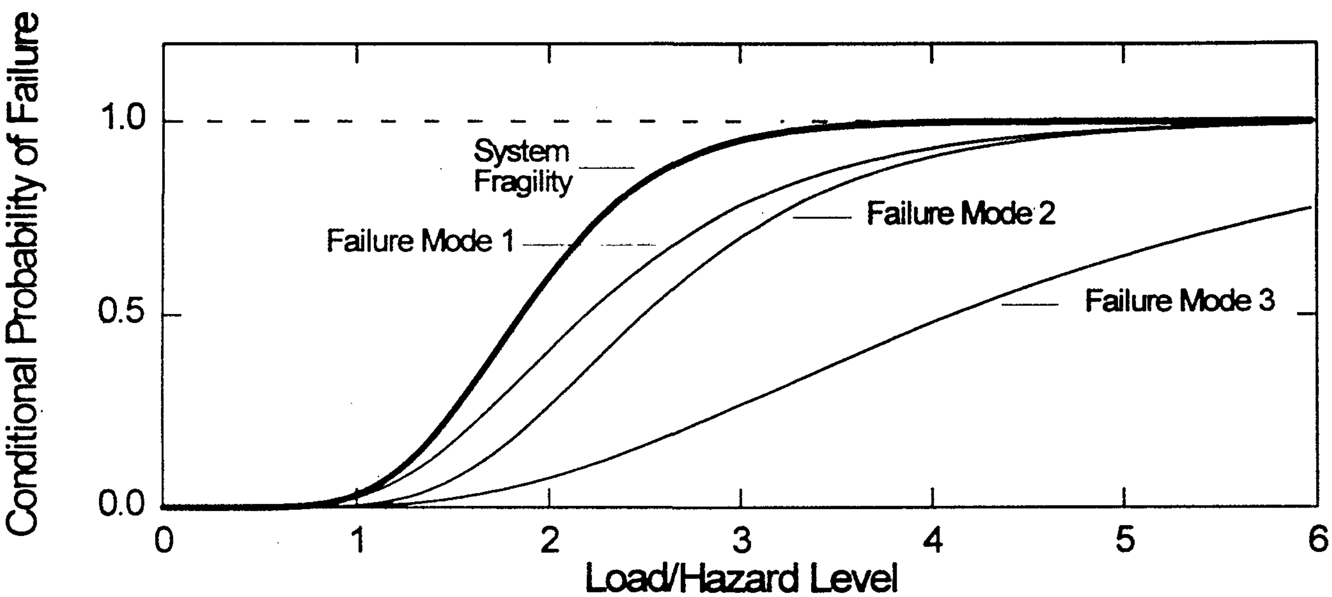

Figure 4-5 An example of a system fragility curve as compared to the fragility curve for individual failure modes.

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5. SEISMIC ANALYSIS

5.1 Overview

This section presents the results of the seismic risk evaluation for the dams considered in the four ESP systems. The SG for seismic events is $9x10^{-7}$. It is important to note that the seismic analysis is performed for each dam site and not on a specific dam structure (type). For each dam site, the seismic capacity required to satisfy the SG is determined. The seismic capacity of a dam is expressed in terms of a required or limiting fragility curve.

The seismic hazard results for the three dam sites are provided in Section 5.2. In Section 5.3 the format of the seismic fragility is described. The results of the risk calculations and the estimate of the required seismic capacity for each site is provided in Section 5.4. Section 5.5 presents a simple seismic systems model. The model is used to identify important considerations for design of a dam in order to meet the seismic SG.

5.2 Seismic Hazard

For each dam site considered in the alternative ESP systems a probabilistic seismic hazard assessment (PSHA) was performed (12, 13). The PSHA included an uncertainty assessment, therefore the mean PGA hazard curve is used to estimate the mean frequency of seismically initiated dam failure. Each PGA hazard curve was defined to a maximum of 1.25g. To perform the risk calculations it was necessary to extrapolate the hazard curve to 2.0g. The extrapolation was based on the log-log slope of the hazard curve in the 1.0 to 1.25g range. Figure 5-1 shows the extrapolated mean PGA hazard curves for the three sites.

5.3 Required Seismic Capacity

As described in Section 4, knowing the seismic SG and the hazard at a site, the required seismic fragility (e.g., the seismic capacity) is determined. This seismic fragility is the lower bound on the seismic capacity that must be provided. By definition, if the seismic fragility of a dam is less than this limiting curve the seismic risk will exceed the SG.

The fragility curve that defines the seismic capacity of civil/structural systems is typically modeled by a Lognormal complementary probability distribution function (3, 14). The Lognormal fragility curve is defined by two parameters, a median, $\overline{A}$, and a logarithmic standard deviation, β. The median capacity, $\overline{A}$, is the best estimate of the ground motion that leads to failure. The logarithmic standard deviation, β, quantifies the variability in material properties and in the response of a dam to earthquake ground motion. The mean fragility curve is defined by $\overline{A}$ and the composite standard deviation, β_c. The composite standard deviation quantifies the total variability, including randomness and uncertainty, in the response of a dam to earthquake shaking.

The composite standard deviation quantifies the total variability, both randomness and uncertainty, in the performance of a dam to earthquake ground shaking. To estimate the required seismic fragility for a dam, both the median capacity, $\bar{A}$, and the composite standard deviation, β_c, must be determined. To determine the required fragility, a value for β_c is assumed and the required median capacity, $\bar{A}$, is calculated.

The estimate of the median capacity depends on the value of β_c that is selected. When β_c is small, the fragility curve will be steep, rising sharply from 0 to 1.0 over a small range of ground motions. As β_c increases, the seismic fragility curve tends to flatten out, rising slower from 0 to 1.0. In terms of the required seismic fragility for a dam, the median capacity will increase as β_c increases. This relationship between $\bar{A}$ and β_c can be understood from the following perspective. Consider a fixed value of $\bar{A}$, the median capacity and a series of seismic fragility curves (centered on $\bar{A}$), with varying values of β_c. For the larger values of β_c the lower tail of the seismic fragility curve (at ground motions less than the median capacity) has higher conditional failure probabilities than fragility curves based on smaller values of β_c. In terms of estimating the frequency of failure, the seismic hazard curve increases substantially with decreasing ground motion level. As a result, with increasing β_c, there is an increased contribution to the frequency of failure of the lower ground motions (as compared to the contribution based on lower β_c values).

Considering the problem of estimating the required fragility for a dam, as higher values of β_c are assumed, higher median capacities are required. From an engineering perspective this translates into higher calculated factors of safety in the design. Alternatively, as lower values of β_c are assumed, the required median capacity is less.

Values of β_c for civil/structural systems vary from approximately 0.33 to 0.55 (14-16). This variation depends on a number of factors such as the type of system (e.g., a dam, nuclear power plant), the number of failure modes that contribute to the likelihood of failure and the uncertainty in estimating the ground motions that can cause failure.

For purposes of this analysis β_c was assumed to be 0.35. The sensitivity of the results to this value is discussed in the next subsection. A number of factors contribute to this assumption. First, estimates of β_c toward the upper end of the range quoted above, tend to be values based on single failure mode assessments of structure failure. Analyses of systems with multiple failure modes will lead to smaller β_c values (and lower median capacity values as described in Section 4.4). Given that multiple seismic modes of failure exist for a dam, lower values of β_c should be used.

A second consideration focuses on the purpose of this analysis. An objective is to determine an achievable seismic fragility for dams at the three sites considered. In this context, assuming a value of β_c, and thus the required median capacity, establishes a fragility curve that must be satisfied. A value for β_c can be interpreted as a limit on the uncertainties that can be tolerated in the design and construction of a dam. The lower the value of β_c, the more stringent the requirement to provide a high degree of reliability at relatively high ground motions. This standard (e.g., low uncertainty) is believed to be achievable on the basis of the high technical standards and degree of care that will be imposed during the design and construction phases.

5.4 Seismic Risk Results

Assuming a value for the median capacity, $\overline{A}$, of a dam and the composite standard deviation, β_c, an estimate of the mean frequency of failure due to seismic events is determined. If the estimated frequency of failure is greater (or less) than the seismic SG, the median capacity must be increased (decreased) and the process repeated. This is continued until a median capacity is determined such that the seismic SG is met.

Table 5-1 lists the required median capacity for each dam site. As a point of reference, the table also lists the proposed seismic design PGA and the required factor of safety for each site. As noted in Section 2, the factor of safety listed in Table 5-1 is different from a factor of safety calculated as part of a design evaluation. The required factor of safety is based on the best estimate of ground motion required to cause sufficient damage to a dam such that uncontrolled release of the reservoir could not be prevented from occurring (e.g., the median PGA capacity).

Table 5-1

Required Seismic Capacity of ESP Dams

Site	Required Median PGA Capacity (g)	Proposed Seismic Design (g) (17)	Required Factor of Safety
Moosa South	1.74	0.66	2.71
Olivenhain	1.42	0.38	3.74
San Vicente	1.32	0.33	4.00

The median capacity values and the factors of safety in Table 5-1 correspond to a system fragility curve for a dam which includes all modes of failure leading to uncontrolled release of the reservoir. For embankment structures this generally corresponds to deformations that lead to overtopping or sufficient damage leading to post-event instability (e.g., flow-through forces, piping). For concrete dams the critical failure modes are sliding, structural damage, foundation failure, and overturning.

Figure 5-2 shows the "required" seismic fragility curves for each dam site. These curves define for a site, the boundary between seismic fragility curves that satisfy the seismic SG and those that do not (see Fig. 4-3). Based on this requirement, the fragility curve can be used to determine the reliability that is required at different PGA levels. At all three sites the chance of failure must be low (less than 0.10) for ground motions less than approximately 1.20g.

The estimate of the Required Median PGA Capacity was based on an assumed value for β_c of 0.35. The sensitivity of the results to this assumption were considered. Figure 5-3 shows the variation in the required median capacity at the three dam sites as a function of result of β_c.

At the Moosa South site, the median capacity increases from 1.74 to 2.99 as β_c increases from 0.35 to 0.55. At San Vicente, the median capacity varies from 1.32 to 1.93. From these results, it is apparent that the assumed value of β_c has an important impact on the required median capacity that is estimated.

From the integration of the hazard and required seismic fragility curves, the relative contribution of different ground motion levels to the frequency of failure can be determined. At all three sites, 85 percent of the contribution to the frequency of failure is attributed to PGA levels of approximately 1.0g or less. For all three sites, 1.0g is less than the required median capacity of the dam. This indicates that the seismic risk is dominated by the lower tail of the fragility curve (to the left of the median capacity, see Fig. 5-2).

Alternative ESP System 25 - This alternative is the only one of the four under consideration that consists of more than one dam. In this case dams are proposed for the Olivenhain and San Vicente sites. With two new or expanded structures included in the system, the risk of a dam failure is greater than for a similar system that consists of only one of the two dams. To address this situation, an evaluation was performed to assess the added risk when there are two new dams as part of the system design. Based on an approximate, conservative assessment it is estimated that the risk of a dam failure due to seismic events is less than a factor of two greater than the seismic safety goal. This is considered a small increase in view of the conservatism in the calculation and the preliminary nature of this study.

5.5 Seismic Systems Model

To examine the factors that are important to the seismic performance of dams, a simple logic tree was constructed. The model considers the following top events:

- level of earthquake damage
- post-earthquake investigation
- mitigating action, and
- post-earthquake stability.

Figure 5-4 shows the seismic logic tree. The purpose of the logic model is to consider the potential for dam failure that could occur as a result of the catastrophic failure of a dam, or in the period immediately following the earthquake (18). Each top event is defined below.

Earthquake Damage - Four levels of damage are considered; catastrophic, heavy, minor, and no damage. Given an earthquake, the performance of a dam can be categorized into any one of these four damage states. Catastrophic damage corresponds to a level of damage that results in immediate release of the reservoir. Heavy damage refers to damage that leaves the dam in a meta stable condition and likely to fail if mitigating action is not taken to reduce the loads on the structure. Minor damage corresponds to damage that has a limited structural impact, but could potentially lead to reduced stability in the long term following the earthquake, if it is not addressed. Lastly, no damage refers to the case where no structural damage has occurred. For all but the no damage condition a fragility curve must be defined that quantifies the likelihood that ground motions will cause damage corresponding to a particular state.

Post-Earthquake Investigation - This event corresponds to the reliability of a post-earthquake investigation to correctly identify the severity of the damage at a dam.

Mitigating Action - This event corresponds to the ability to lower the reservoir in a timely manner following the earthquake in order to reduce the loads on the dam. The ability to lower the reservoir depends on the level of damage and the functionality of the outlet works. In the model an assessment of the reliability of the outlets and the time to lower the reservoir is not made. Rather, this event is modeled to assess its level of importance in the analysis and the performance of the dam.

Post-Earthquake Stability - If a dam has been damaged, it may be more likely to fail as a result. The likelihood that the dam will be unstable depends on the damage to the dam and the reservoir level immediately following the earthquake (e.g., success of mitigating actions).

The logic tree in Figure 5-4 was evaluated on the basis of a subjective assessment of the event state probabilities. The analysis was not performed for a particular dam. Rather a quantification was performed to assess the relative importance of the different top events.

The quantification of the logic tree in Figure 5-4 provides insights into the relative importance of the top events. Another product is an estimate of a system (total) seismic fragility curve for a dam.

5.5.1 Logic Tree Input

Figure 5-5 shows the seismic fragility curves that were used to model the different damage states. To cause minor structural damage, a median PGA capacity of 0.50g was assumed. For heavy damage, a median capacity of 1.0g was used and for catastrophic failure the median was 1.74g. (Note, for illustration purposes, the median capacity for catastrophic failure was selected as the required median capacity for the Moosa South site.)

The other inputs to the model are listed in Table 5-2. These inputs were selected to provide an order of magnitude sense of the dominant sequences and events. The probabilities listed in Table 5-2 correspond to the failure or unsuccessful performance of the action or event listed. The probability of success or satisfactory performance is simply one minus the probability of failure.

5.5.2 Results

Figure 5-6 shows the total system seismic fragility curve for a dam with the fragility curve for catastrophic damage. A number of important observations can be made from this figure. First, the total system fragility curve, which is based on all of the logic tree sequences that lead to dam failure, has a somewhat lower median capacity (1.66 versus 1.74g PGA) than the catastrophic damage state fragility curve. This is due to the fact that the total system fragility curve accounts for additional modes of failure. As a result, the overall capacity of the dam is lower.

The implication of this result is that the fragility of the dam for individual modes of failure (e.g., sliding, embankment stability, etc.) must have seismic capacities that are greater than the required seismic fragility for a site, otherwise the total seismic fragility for the dam will not satisfy the seismic SG.

A second observation from the logic tree quantification concerns the potential for failure following a seismic event, assuming a catastrophic failure does not occur. If failure is likely to occur at ground motions less than approximately 1.30g PGA, meeting the required seismic fragility curve for a site may be jeopardized. In the example calculation, the risk of failure is dominated by ground motions less than 0.57g PGA. For the Moosa South site the seismic risk was dominated by ground motions in the range 0.50 to 1.30g PGA. Effectively, the potential for failure given minor or heavy damage represents additional, weaker failure modes that contribute to a lower, total system fragility for the dam.

Table 5-3 lists the percent contribution of each sequence in the logic tree to the total frequency of failure. The total frequency of failure is determined as the sum of the individual sequence frequencies for those sequences that lead to failure. These results should be viewed in the context of providing an insight to factors that can contribute to the vulnerability of a dam that experiences strong ground motion. Clearly, an evaluation of the logic tree for a specific structure could potentially lead to different results. The focus here is to identify factors that could adversely impact the ability of a dam design to meet the SG.

The results in Table 5-3 indicate that in addition to catastrophic failure, the sequences involving heavy and minor damage are important contributors to the seismic risk. When heavy or minor damage does occur, it is important that an accurate assessment of the severity of the damage be made and that the appropriate mitigating steps be taken to reduce the loads on the dam. Failure to do so leaves a dam particularly vulnerable.

Historically, the response following a seismic event in California has been effective. In most cases either the dam owner, their consultant and/or the state dam safety engineer will inspect a dam immediately following an earthquake. When problems are discovered, they are addressed and remedied. Consequently, the likelihood of minor damage initiating a chain of events that result in dam failure is considered unlikely.

Table 5-2

Summary of the Seismic Logic Tree Event Probabilities

Event	Probability[1]
Post-Earthquake Inspection Following Minor Damage	0.30
Post-Earthquake Inspection Following Heavy Damage	0.10
Mitigating Action - Following Minor Damage	0.05
Mitigating Action - Following Heavy Damage	0.10
Post-Earthquake Stability - Following Minor Damage and Successful Identification of the Earthquake Damage	0.001
Post-Earthquake Stability - Following Minor Damage and Unsatisfactory Identification of the Earthquake Damage	0.005
Post-Earthquake Stability - Following Heavy Damage and Successful Identification of the Earthquake Damage	0.01
Post-Earthquake Stability Following Heavy Damage and Unsatisfactory Identification of the Earthquake Damage	0.05

[1] The event probability corresponds to the unsuccessful or unsatisfactory outcome of the event.

Table 5-3

Summary of Sequence Contribution

Sequence No.[1]	Sequence Description	Percent Contribution To Seismic Risk[2]
1	Minor damage, followed by unsuccessful mitigating action	0.6
2	Minor damage, followed by failure of the post-earthquake inspection to correctly identify the damage	26.8
3	Heavy damage, followed by unsuccessful mitigating action	7.4
4	Heavy damage, followed by failure of the post-earthquake inspection to correctly identify the damage	41.1
5	Catastrophic failure	24.1

[1] Refer to Figure 5-3 for the sequence numbers.
[2] Calculated as: (Sequence Frequency/Total Frequency of Failure) * 100%

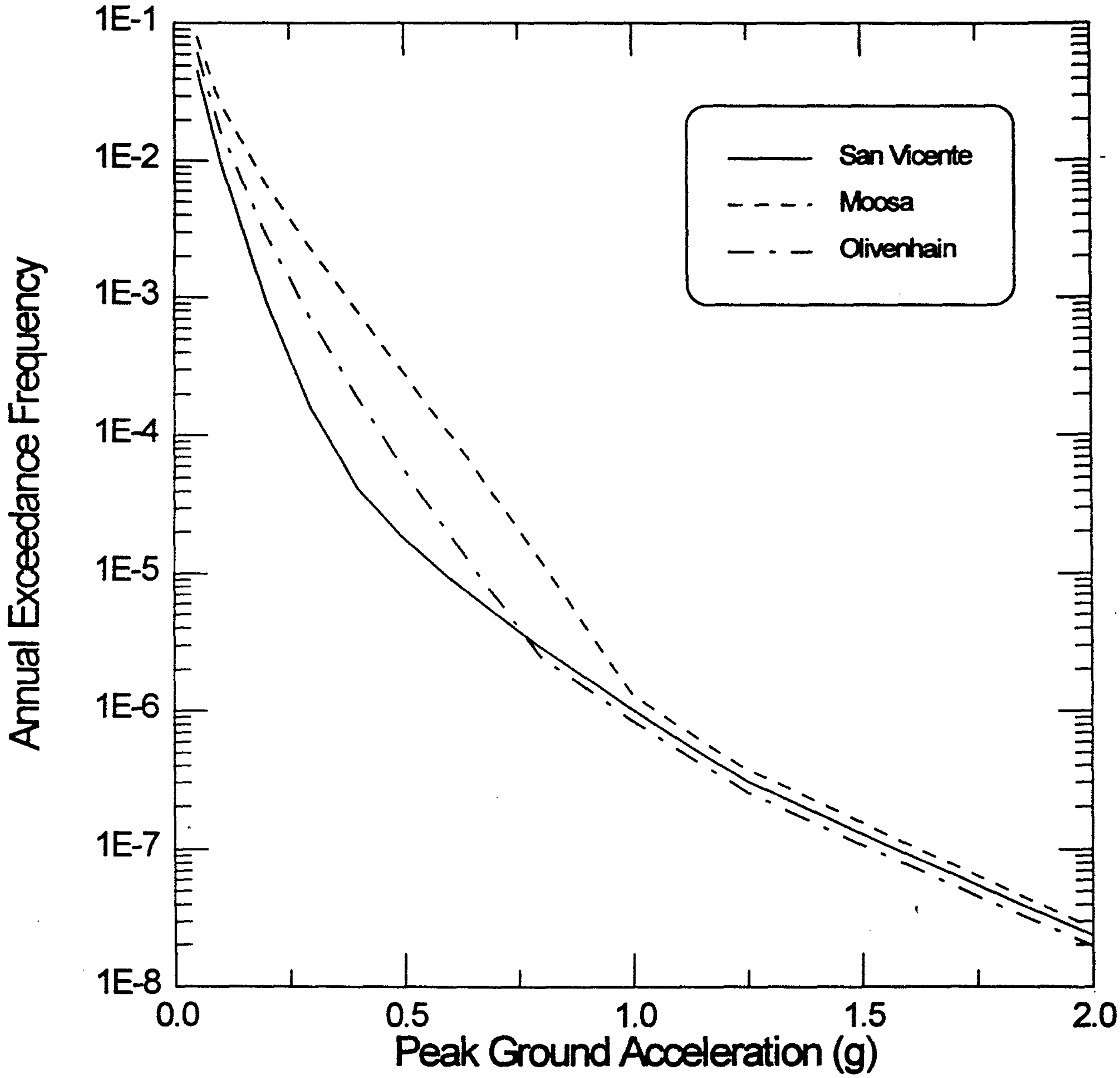

Figure 5-1 Mean PGA hazard curves for the Moosa South, San Vicente, and Olivenhain sites.

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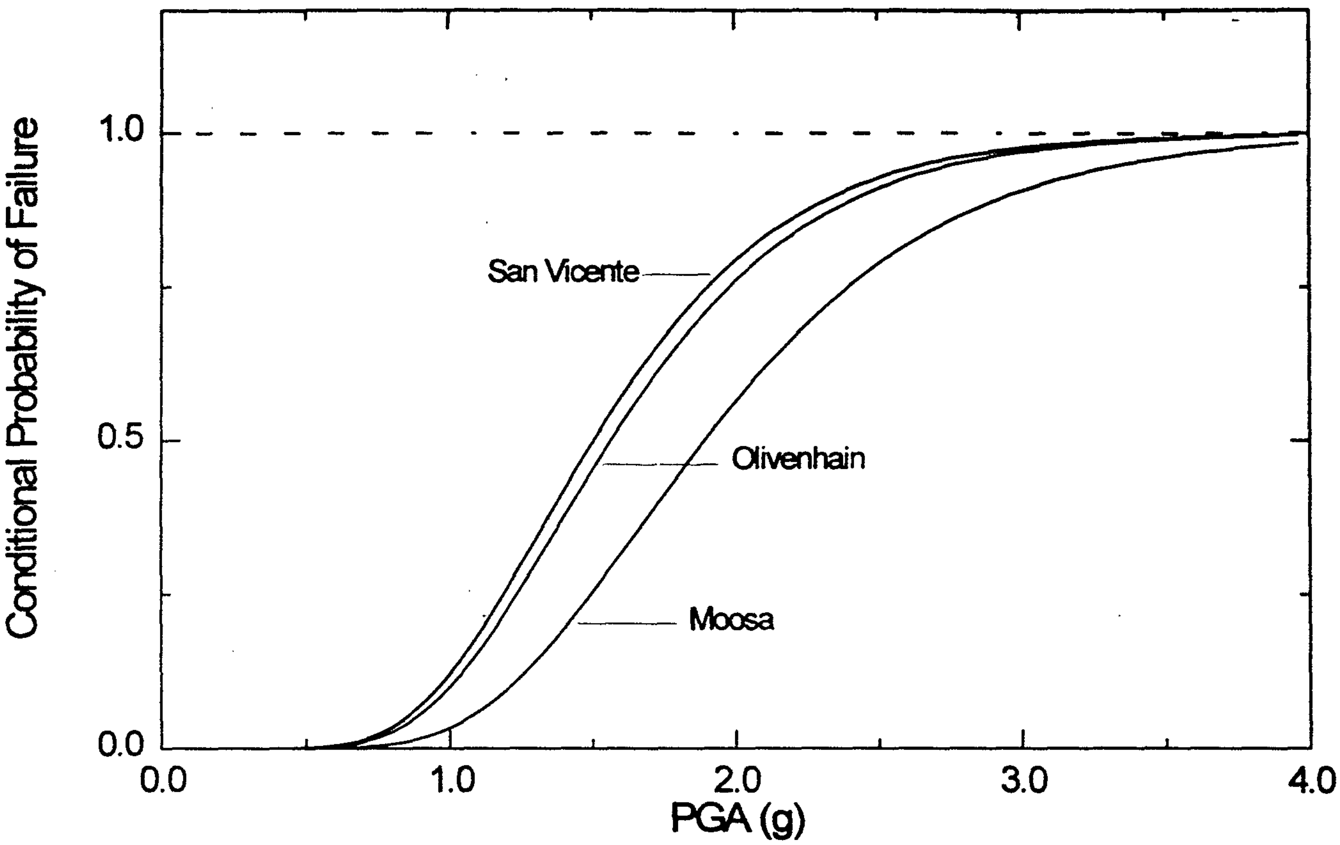

Figure 5-2 Required seismic fragility curves for the three dam sites.

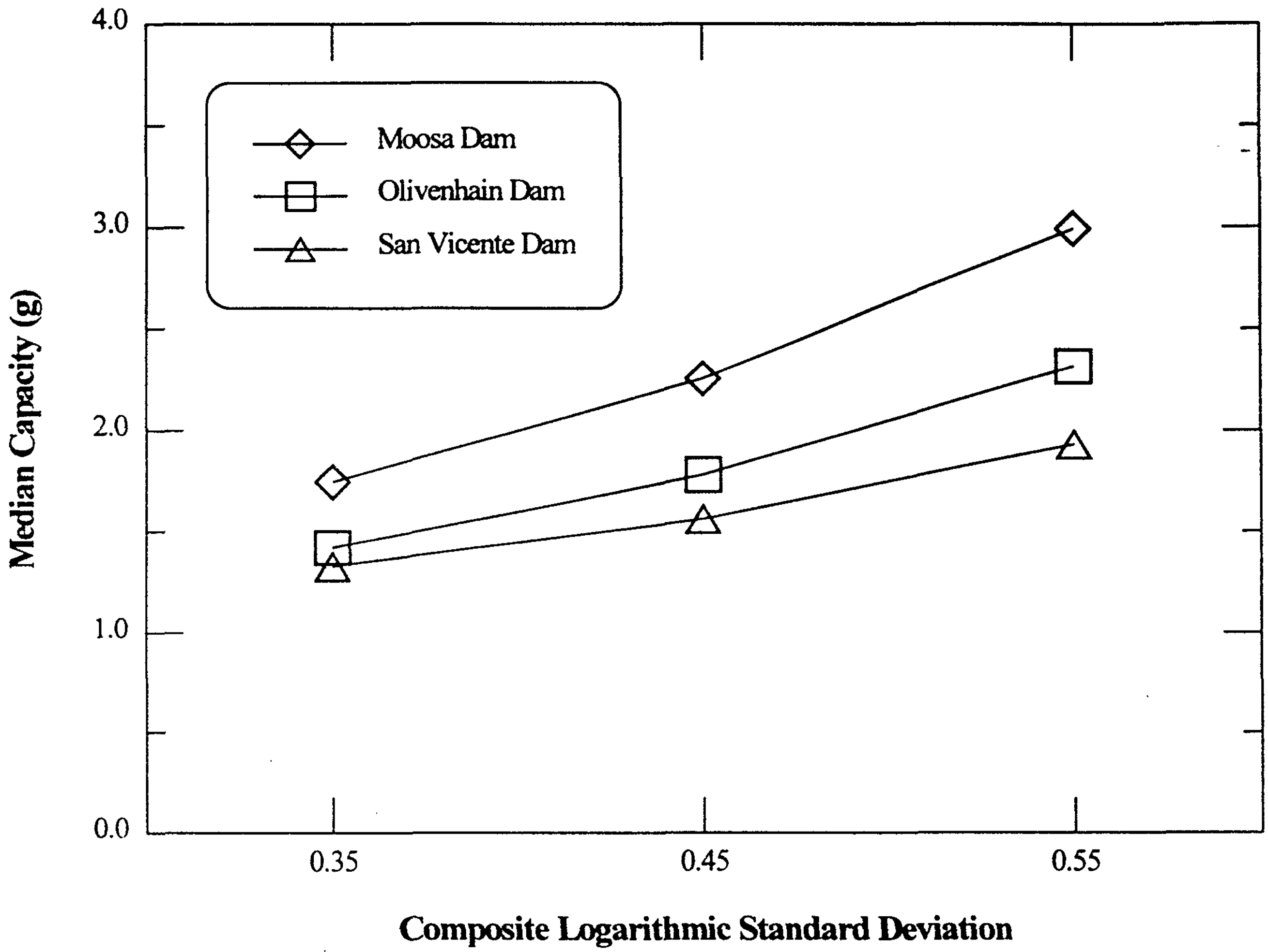

Figure 5-3 Variation of the required median seismic capacity at the three dam sites as a function of the composite logarithmic standard deviation.

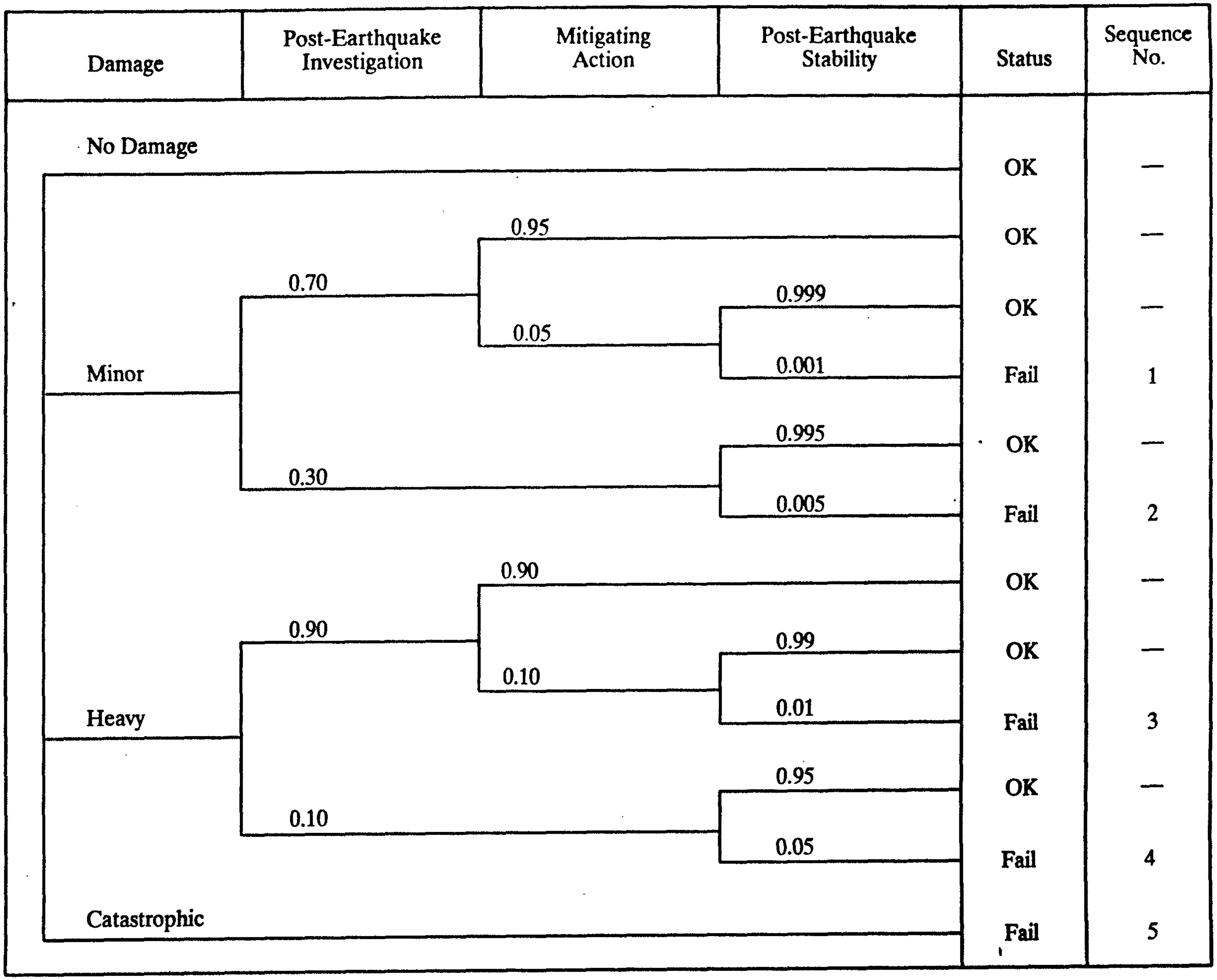

Figure 5-4 Seismic systems logic tree.

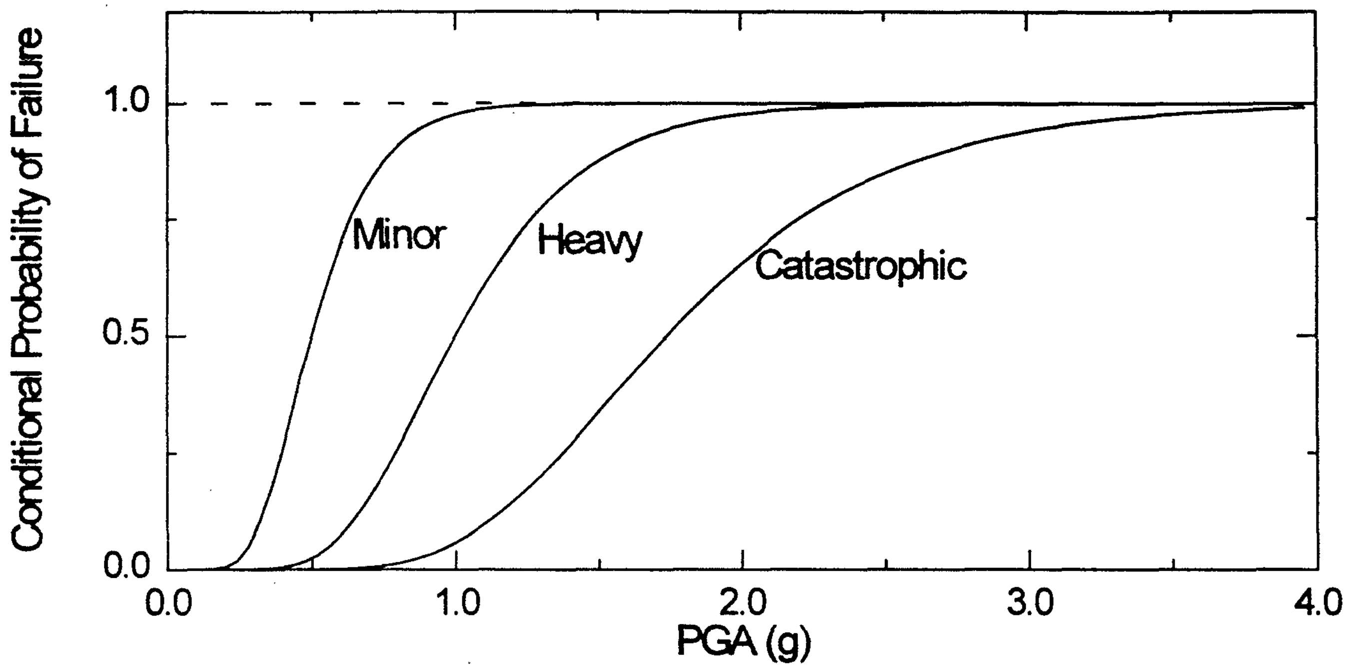

Figure 5-5 Illustration of the seismic fragility curves used to quantify the seismic logic tree.

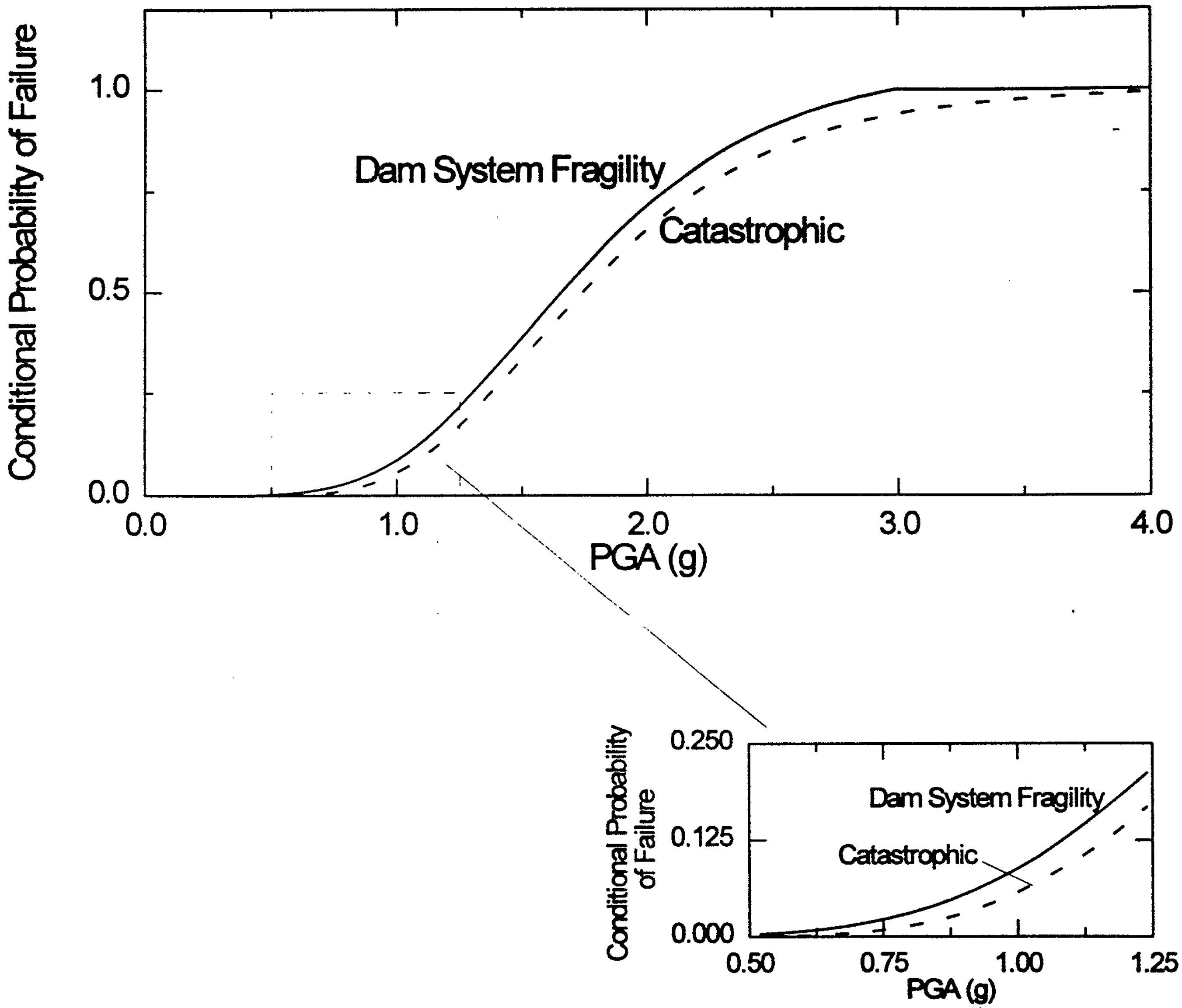

Figure 5-6 Comparison of the seismic system fragility curve derived from a quantification of the seismic system logic tree and the fragility curve for catastrophic failure.

6. HYDROLOGIC ASSESSMENT

6.1 Overview

Unlike the assessment that was performed for seismic events, the results of site-specific probabilistic evaluations of the frequency of inflow floods are not available. As a result, the frequency of occurrence of lateral and/or hydraulic loads that a dam might experience due to inflow floods is not known. According to the California Division of Safety of Dams criteria, the Inflow Design Flood (IDF) for the ESP dams is the Probable Maximum Flood (PMF). Traditionally, engineers have assumed that dams designed to the PMF have no chance of failure due to overtopping. However, as noted by the ASCE task committee on Spillway Design Flood Selection, a dam designed to the PMF does not provide a guarantee that dam failure will not occur (19).

Just as in the seismic case, it is necessary to determine the required hydraulic/structural capacity of a dam and spillway system that must be provided in the design. However, unlike the seismic analysis two basic variables are unknown:

- the frequency of floods greater than the IDF, and
- the hydraulic and structural capacity of the dam and spillway system.

In the analysis an assumption with respect to the frequency of large floods must be made. If the frequency for the PMF is assumed to be relatively high, the hydraulic and structural capacity of the dam and spillway must have a relatively high factor of safety to meet the hydrologic SG. Alternatively, if the frequency of exceedance of the IDF is low, a relatively low factor of safety is required to meet the same goal.

Figure 6-1 shows the relationship between the flood frequency curve and the hydrologic fragility curve for a dam. Both curves are defined in terms of a common measure of the flood hazard at a site. For purposes of this analysis the flood is defined in terms of the IDF Load. The IDF Load represents loads on the dam derived from the IDF. (Note, in practice, the flood hazard might be defined in terms of the reservoir elevation, peak inflow discharge, or other appropriate characterization.) Noted on the figure are key variables considered in the hydrologic analysis:

ν(IDF Load) = frequency of exceeding the IDF Load

P(f | IDF Load) = conditional probability of dam failure given the IDF Load

$\overline{\text{IDF}}$ Load = median hydrologic capacity of the dam

α = log-log slope of the flood frequency curve beyond the IDF Load

The conditional probability of failure defines the reliability that must be provided in a design for loads defined in terms of the IDF Load. This assessment assumes the frequency of dam failure due to floods less than the IDF Load is negligibly small.

6.2 IDF and Flood Frequency

As part of this assessment it is assumed that the PMF is not the largest flood that is physically possible in a watershed. Therefore, there is a frequency that the PMF can be exceeded.

Two cases are evaluated with respect to the frequency of extreme floods (e.g., greater that the PMF). These cases are listed in Table 6-1.

Table 6-1

Assumptions For the Frequency of Large Floods

Case	Annual Frequency of Exceedance of the IDF Load, ν(IDF Load)	Slope of the Flood Frequency Curve, α
1	10^{-4}	10
2	10^{-6}	10

It is assumed that for each dam site the same meteorologic and hydrologic phenomena prevail. On this basis it is assumed that the frequency of exceeding the IDF Load is the same for each dam.

As in the seismic analysis, a top-down approach is used to determine the capacity that must be provided to sustain the loads associated with the inflow flooding to a site.

6.3 Hydrologic Fragility

The hydrologic fragility of a dam defines the conditional probability of failure given the magnitude of the hydrologic event which is characterized in terms of the IDF Load. The fragility of a dam system is expressed as a function of the IDF.

It is assumed that the hydrologic fragility of a dam is defined by a Lognormal distribution function. The Lognormal fragility has two parameters, the median capacity and the logarithmic standard deviation, β.

To estimate the required fragility for hydrologic events, a value of $\beta = 0.22$ was assumed. Based on trial and error (similar to the seismic analysis), an estimate of the median capacity was determined. The sensitivity of the median capacity to the assumed value of β was also checked.

6.4 Results

Table 6-2 lists the required median capacity for the two assumptions on the frequency of exceeding the IDF Load. The estimate of the median varies depending on the value of β that is used. For example, if β is assumed to be 0.30, the median capacity increases to approximately 2.1, when the frequency of the PMF is 10^{-6}. Figure 6-1 shows the required hydrologic fragility curves for each case.

When the frequency of the PMF is 10^{-6} per year, the required median capacity corresponds to the factor of safety often required in design. As a result, satisfying the SG should be readily achievable. On the other hand, if the frequency of exceeding the PMF is 10^{-4} per year, the required median capacity is higher, 2.7. This exceeds typical factors of safety used in design.

The sensitivity of the results to the slope of the flood frequency curve was considered. It was concluded that the slope had a small impact on the results. The primary factor was the assumed frequency of the PMF.

Table 6-2

Hydrologic Risk Assessment Results

Case	Frequency of Exceedance of the IDF Load	Required Median FOS[1]
1	10^{-4}	2.7
2	10^{-6}	1.8

[1] FOS - Factor of Safety

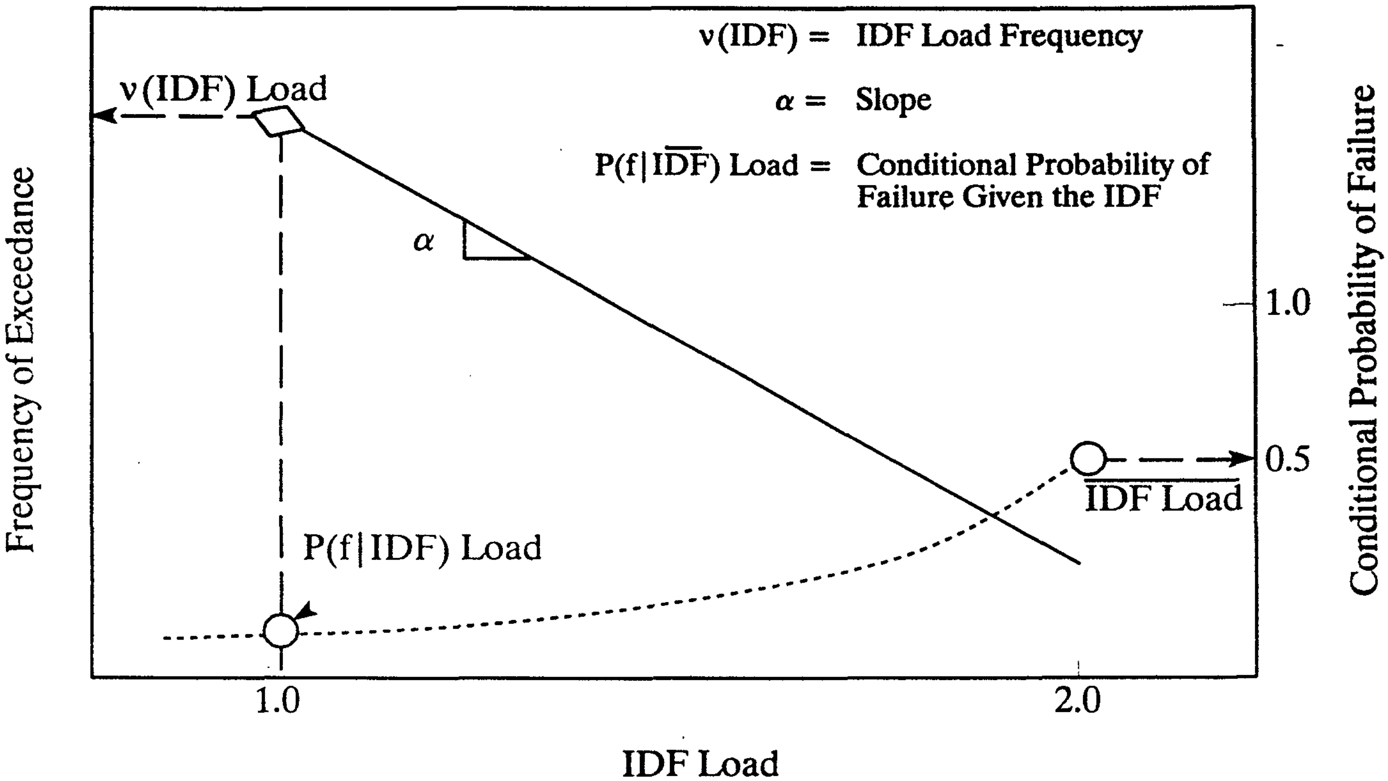

Figure 6-1 Illustration of the relationship between the flood frequency and the hydrologic fragility curve.

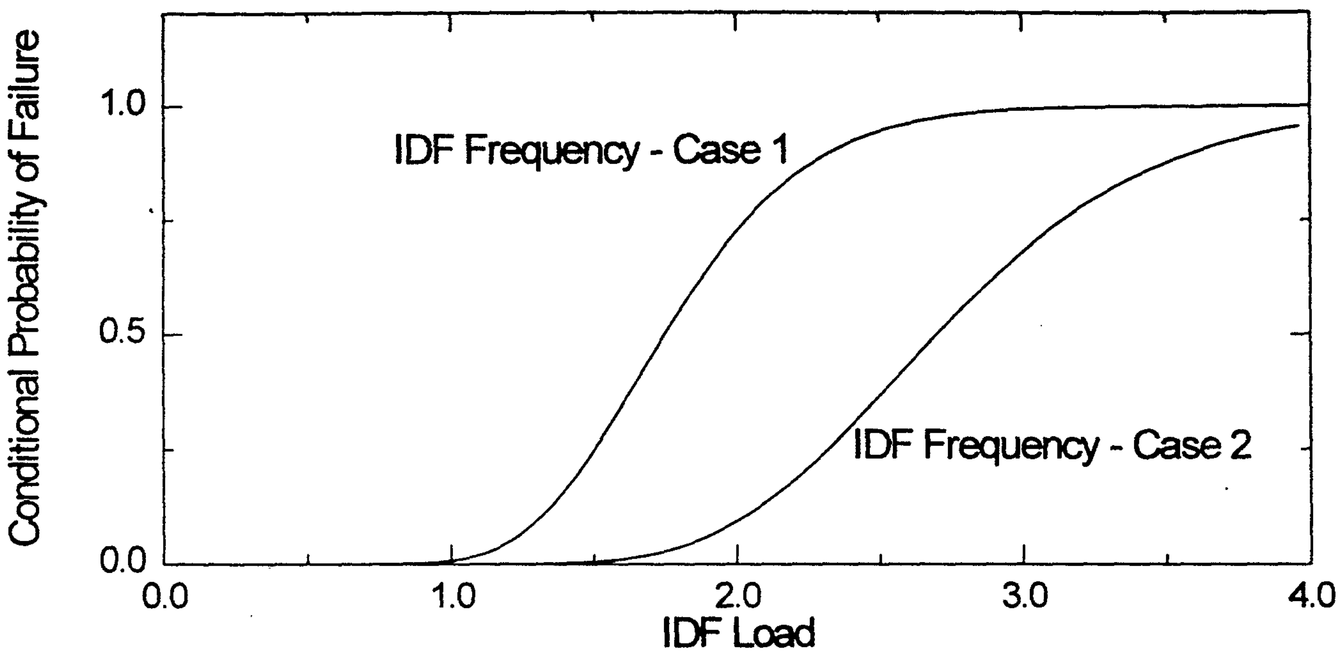

Figure 6-2 Required hydrologic fragility curves for the two assumptions regarding the frequency of exceeding the PMF.

7. OTHER MODES OF DAM FAILURE

7.1 Overview

This section addresses the risk of dam failure due to all other failure modes. This assessment is based in part on a logic tree model and a comparison to historic experience.

7.2 Historic Experience and Dam Failure Rates

The historic performance of dams provides insights to the factors that have contributed to dam failures and to the frequency of their occurrence. The lessons from past experience suggest that many failures have occurred as a result of inadequate site investigation and/or poor design or construction. The benefits of these lessons have contributed greatly to improved methods of dam engineering to reduce the vulnerability of dam to failure.

Table 7-1 lists the historic dam failure frequencies for concrete and rockfill dams in the U.S. (10). The frequencies listed in the table do not include seismic, hydrologic or wave-related events. Also excluded are dam failures that occurred in the first five years of operation which is the period during initial filling and operation of a reservoir. The frequency estimates in Table 7-1 are based on an analysis that accounted for the variation in the frequency of failure over time. As methods of dam design and construction improve over time, it is reasonable to expected that the average time (e.g., number of dam years of operation) between failures would increase. This should be indicative of the improved reliability of the structures that are built. The statistical analysis performed in Reference 10 accounts for the possibility that the overall frequency of dam failure may be decreasing as methods of design and construction have improved.

Table 7-1

Historic Dam Failure Frequencies

Dam Type	Frequency (per year)
Concrete	3.1×10^{-5}
Rockfill	3.5×10^{-5}

These estimates of the historic frequency of dam failure are based on a broad population of conditions that fit into a general category of dams. Within the population there is a wide range of site conditions, design methods, and construction techniques that are represented. As a result, empirical estimates of the frequency of dam failure cannot be used as an estimate for a specific structure. At the same time however, historic estimates can provide a benchmark for structure specific evaluations.

7.3 Safety Goal Requirement

The SG requirement for all other modes of dam failure is $6x10^{-8}$ per year. For purposes of this assessment, it is assumed that the dominant modes of failure in this category are failures associated with foundation problems, seepage/piping, stability (under static loads) and structural performance. All other potential modes of dam failure are assumed to be non-existent at a site (e.g., flooding resulting from an upstream dam failure) or the design is sufficient to conclude that risk of failure is negligible (e.g., failure due to overtopping events created by wind waves, seiche or landslide in the reservoir).

7.4 Risk Evaluation

In a relative sense the ESP dams must be designed and constructed such that the frequency of failure is approximately a factor of 1000 less than the performance of dams historically. The ability to achieve this level of reliability is founded in the benefits of extensive site investigations, the development of design and construction specifications that provide high confidence that adverse conditions are identified and reliable defensive mechanisms are implemented.

To evaluate the factors that must be considered to provide a required level of reliability, a logic model is developed. The purpose of the logic model is to provide insights into the role that the site investigation and the design and construction process have on the overall reliability of a dam. The logic tree is not used to evaluate a specific type of structure, rather to identify the importance of different factors in determining the rate of dam failure. Figure 7-1 shows the logic tree. The logic tree defines 14 sequences or combinations of events that impact the reliability of a dam.

The top events in the logic tree are:

Adverse Site Conditions - This event refers to the likelihood that adverse geologic or geotechnical conditions may exist at a site that require special consideration during the design and construction process.

Site Investigation - The purpose of a site investigation is to accurately and completely characterize the conditions at a site. If the site investigation fails to adequately characterize a site or to identify adverse site conditions, incomplete or erroneous information is used in the design process. This event corresponds to the reliability of the site investigation.

Design and Construction - This event refers to the possibility that the design or construction of a dam is not satisfactory, resulting in a significant vulnerability that compromises the integrity of the structure. Historically, design and construction deficiencies have been identified as contributors to dam failure. This event quantifies the likelihood of a design or construction deficiency.

Identification of Problems During Initial Filling - When problems at a site or with a design occur, they are often identified during the initial filling of the reservoir. This event refers to the likelihood that problems with the design or construction of a dam will be observed and correctly diagnosed during the initial filling period.

Remedy Problems - If a problem at a dam is identified during the initial filling, this event refers to the success or failure of attempts to remedy the problem. In a practical sense, the ability to remedy the problem depends on a number of factors such as the type and severity of the problem, the difficulty in implementing a solution, etc. In this analysis a subjective estimate of the probability of failing to remedy a problem is made.

Dam Failure Frequency - This event corresponds to the frequency of dam failure, conditional on the status of prior events. For example, consider Sequence 1, where there are no adverse site conditions or design/construction deficiencies. The frequency of dam failure in this case is very different from Sequence 4 where a design/construction deficiency exists.

Each sequence in the logic tree defines a combination of events that impact the reliability of a dam. The first five top events in the logic tree define the conditions under which the dam is finally placed in service and the final event quantifies the reliability of the dam, given the existing conditions.

7.5 Logic Model Input

Table 7-2 lists the event probabilities used to quantify the logic tree. The probabilities were subjectively assigned. For purposes of this study, the dam failure frequencies denoted DF1, 2, 3 and 4 are defined as a multiple of the historic failure rate. These are conditional failure frequencies that depend on the conditions or events that proceed it. For purposes of this application the failure rate of concrete dams is used.

7.6 Results

Table 7-3 lists the frequency of dam failure for each logic tree sequence. The results of the logic tree quantification provide a number of insights into meeting the SG for other events. Based on the input listed in Table 7-2, the dominant sequence (Sequence 1) has a frequency of occurrence of approximately $2x10^{-8}$ and involves no adverse site conditions or design or construction deficiencies. Neglecting for a moment the frequency of dam failure, DF-1, this is a high probability sequence (meaning it is likely that an ESP dam site will not pose a substantial problem and the design and construction will be satisfactory). This is reasonable since it is based on a sequence in which there are no adverse conditions and it is expected that the design and construction will be satisfactory. However, when the frequency of dam failure is included in the quantification (DF-1), this sequence has the highest frequency of occurrence. Arguably, this would not be the case, since the chance of failure should be low. However, the insight from this result is clear, the reliability of the design and construction process, even under the most favorable conditions must be far better than historic experience.

Sequence 5 is similar to Sequence 1 in that all aspects of the design/construction process were conducted satisfactorily. In this case the dam is constructed at a site where adverse conditions exist. In some respects, Sequences 1 and 5 represent minimum estimates of the reliability of a dam since they correspond to the frequency of failure when all investigations and engineering activities were performed as expected.

It is important to note that a satisfactory design and subsequent construction of a dam is judged not in an absolute sense, but rather in the context of what the profession correctly believes to be appropriate. To the extent that methods of design and construction change (improve) they do not produce risk free structures, some risk of failure will always exists (Sequence 1).

Each of the remaining sequences has a frequency of occurrence less than 10^{-8} per year. In these sequences there was either an unsatisfactory site investigation and/or an error in the design and construction process. In each case, if the probability of an error or unsatisfactory investigation was higher (e.g., an order of magnitude), the resulting sequence frequency would increase as well. This points to the need for a high quality (and therefore reliable) site investigation and reliable design/construction process. When these conditions exist, the frequency of dam failure, even under unsatisfactory circumstances is low (e.g., see Sequences 13, 14).

In a similar manner, the logic tree points to the benefits of an instrumentation and monitoring program during initial filling of the reservoir. Failure to identify a problem during the first filling is an important event in Sequences 4, 8 and 11. Collectively, these sequences comprise 33 percent of the total frequency of failure. Sequences 1 and 5 make-up 60 percent of the total.

Approximately 5 percent of the remaining risk is contributed by Sequences 7 and 10. In these sequences efforts to repair problems discovered during initial filling are unsuccessful, leading to dam failure.

Table 7-2

Logic Tree Input - Top Event Probabilities

Top Event Description	Probability[1]
Adverse Site Conditions Exist at the Site	0.10
Site Investigation (failure to adequately characterize a site)	0.01
Design/Construction Deficiency Given: No Adverse Site Conditions Adverse Site Conditions	 10^{-3} $5x10^{-3}$
Identification of Problems During First Filling Sequences 2, 3, 4 Sequences 6, 7, 8 Sequences 9, 10, 11 Sequence 12, 13, 14	 0.10 0.05 0.03 0.01
Remedy Problem (Failure to remedy a problem)	0.01
Dam Failure Frequency[2] DF-1 DF-2 DF-3 DF-4	 $3.63x10^{-8}$ $8.73x10^{-8}$ $8.73x10^{-5}$ $2.18x10^{-4}$

[1]Note: The event probabilities are conditional on the events that proceed it in a sequence.
[2]Based on the historic rate of failure for concrete dams.

Table 7-3

Logic Tree Results

Sequence No.	Sequence Description	Frequency
1	No adverse site conditions and no design/construction inadequacies	3.26E-08
2	No adverse site conditions and design/construction inadequacies remedied	2.91E-11
3	No adverse site conditions and design/construction inadequacies not remedied	7.07E-10
4	No adverse site conditions and design/construction inadequacies not identified	7.86E-09
5	Adverse site conditions identified and no design/construction inadequacies	3.58E-09
6	Adverse site conditions identified and design/construction inadequacies remedied	4.06E-11
7	Adverse site conditions identified and design/construction inadequacies not remedied	1.03E-09
8	Adverse site conditions identified and design/construction inadequacies not identified	5.40E-09
9	Adverse site conditions not identified and no design/construction inadequacies, site investigation problem remedied	8.38E-11
10	Adverse site conditions not identified and no design/construction inadequacies, site investigation problem not remedied	2.11E-09
11	Adverse site conditions not identified and design/construction inadequacies, site investigation problem not identified	6.53E-09
12	Adverse site conditions not identified and design/construction inadequacies remedied	8.56E-14
13	Adverse site conditions not identified and design/construction inadequacies not remedied	2.16E-12
14	Adverse site conditions not identified and design/construction inadequacies not identified	2.18E-12

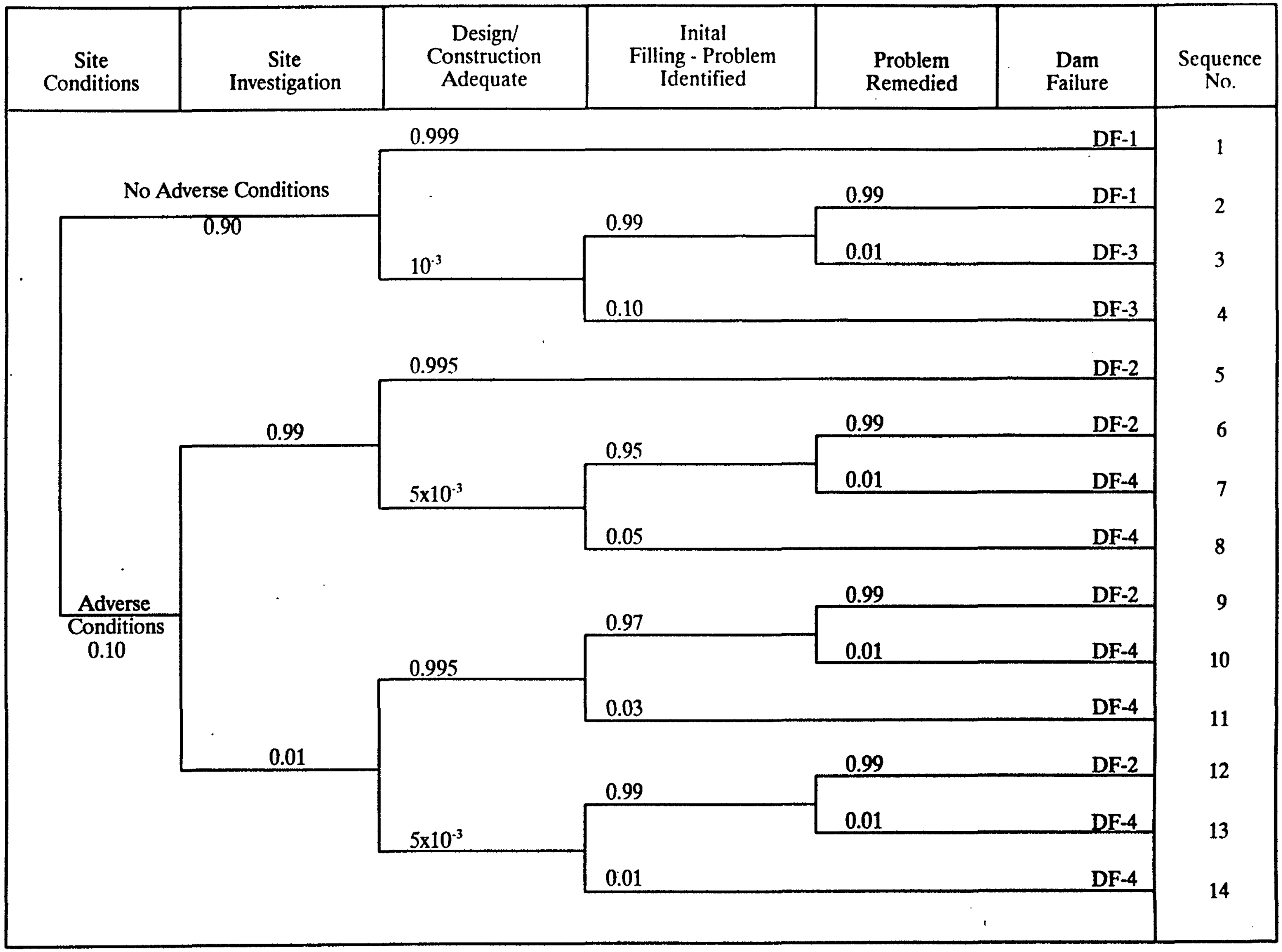

Figure 7-1 Logic tree for evaluating the frequency of dam failure under static conditions.

8. SUMMARY

To facilitate the San Diego County Water Authority planning study for the ESP, a risk-based evaluation was performed in which the objectives were to establish a SG for the performance of dams and to give insights into factors that must be addressed in meeting the goal. This section summarizes the SG evaluation, providing observations and recommendations.

Safety Goal - For dams considered as part of the alternative ESP systems, a SG was specified in terms of the mean frequency per year of dam failure. The SG, which was set to 10^{-6} per year, is the limiting frequency of dam failure due to any cause. It is equal to or less than the safety goal of other critical facilities constructed in the U.S. As a basis to address considerations in the design of a dam, the SG was partitioned among the dominant modes of dam failure. The partitioning was carried out on the assumption that the seismic hazard in the region posed a substantial threat and as a result would be a dominant contributor to the likelihood of failure.

Seismic - For each dam site, a seismic analysis was performed to determine the required or limiting seismic fragility that must be provided for in the design of a dam. The determination of the required fragility is a function of the site seismic hazard and defined safety goal, only. It does not depend on the type or size of dam constructed at a site or how it is operated (i.e., reservoir levels). However, for a particular type of dam, how the seismic safety goal is satisfied will vary.

The required seismic fragility for a dam is a composite or system level fragility curve. To examine the factors that could potentially impact the design of a dam, a logic model was developed. The model consisted of a logic tree whose top events, represent global events that might occur following an earthquake and might influence the seismic reliability of a dam. The following summarizes the observations from the model:

1. At the dam sites considered in the alternative ESP systems, the likelihood of failure is dominated by ground motions in the range 0.60 to 1.30g PGA.

2. To satisfy the seismic SG the conditional probability of failure for ground motions in the 0.60 to 1.30g range must be low. This requirement means that a dam must also have a high capacity (low conditional probability of failure) for levels of damage that do not fail the dam, but make it vulnerable to failure following an earthquake.

3. Facilities to evacuate a reservoir must have a high seismic capacity to provide assurance that a capability exists to reduce loads on a dam following an earthquake.

4. To produce a total system fragility for a dam that satisfies the required fragility, the seismic fragility for individual modes of dam failure (e.g., sliding, stability) must have capacities that exceed the required fragility capacity.

5. The uncertainty in the seismic performance of dams should be reduced to the smallest practical levels in order to provide high confidence that the conditional probability of failure at ground motion as high as 1.3g is low. This can be achieved through quality assurance of the design and construction process. Low failure probabilities can also be achieved by providing high factors of safety in the dam design (or alternatively designing to higher ground motions) and/or by providing features in a design that adds redundancy to the ability of a dam to withstand the affects of ground shaking.

Hydrologic - In comparison to the seismic analysis, the hydrologic assessment was limited in scope due to the fact that an assessment of the frequency of extreme floods was not available for any of the proposed sites. The following summarizes the key observations from the hydrologic analysis:

- Compared to seismic events, the design basis loads for hydrologic events are proportionally high in comparison to the largest events that are postulated. As a result, the factors of safety that are required to meet the SG are reasonably consistent with design practice[2].

- The key to meeting the SG for hydrologic events is knowing the mean frequency of exceedance of the IDF Load. If the mean frequency of exceeding the IDF Load is greater than 10^{-6} per year, the required factor of safety will likely exceed values typically used in design.

In addition to the above observations, it should be noted that the frequency of dam failure due to hydrologic events may not be a reliable surrogate for the risk to the public (recall, this was the overall purpose of the safety goal). This is attributed to the fact that the incremental impact to the public when a dam fails during a hydrologic event may be small. (Note, at this time the incremental flooding and therefore the public risk is not known.)

To incorporate the incremental risk to the public due to a hydrologically initiated dam failure, three steps are required:

- determine the downstream flooding due to outflow from the dam and from a dam break,

- assess the risk to the public, and

- define a safety goal in terms of public health risk.

As part of the assessment of the public risk, the potential for evacuation in the inundated downstream areas must be considered.

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[2] For seismic events the design basis load is typically much smaller than the largest loads that could occur. As a result, high factors of safety are required to provide the necessary level of reliability.

In view of the fact that meeting the hydrologic SG is tied so closely to the frequency of exceeding the IDF, a demonstration that the goal is met at a particular site requires that a comprehensive flood frequency analysis be performed. The benefits of such an analysis are:

1. Provides a defendable estimate of the frequency of extreme floods and the hydrologic risk.

2. Could result in a recommendation for a lower IDF, particularly if the incremental flooding from a dam failure is small.

Other Modes of Failure - The results of the analysis for other modes of dam failure provided the following observations:

1. Overall, the reliability of an ESP dam must exceed the historic experience by at least a factor of 1000. That is the frequency of dam failure must be a factor of 1000 less than the historic rate of failure.

2. In order to provide a reasonable assurance that the design of a dam satisfies the SG, there must be a high reliability associated with the site investigation and the design and construction process.

3. Given a scenario in which there are no errors in the site investigation and there are no design or construction errors, the frequency of failure of a dam must be a factor of 1000 smaller than historic experience.

4. The potential for design and construction could be a limiting factor in the analysis. Removing this potential through quality assurance and design/construction review is vital.

As part of this study, certain assumptions were made regarding the dominant modes of dam failure. These assumptions were made on the following basis:

1. The likelihood of hazards (e.g., seiche, landslide induced floods) whose magnitude is large enough to cause failure is low.

2. The design of dams is conservative (has a high factor of safety) such that the conditional probability of failure is low.

3, Historically, these events (e.g., seiche, wind-waves, landslide induced floods) have not been important contributors to dam failures.

For these conditions to apply, it is important that the design process verify that circumstances do not exist at an ESP dam site whereby these assumptions would not apply.

Meeting the Safety Goal - To provide a reasonable assurance that the SG for a dam(s) designed as part of the ESP is satisfied, it is recommended that a risk assessment be performed in parallel with the design process. From a practical perspective, following standard design practice does not automatically provide an assurance that the SG will be met. In comparison to historic experience, the reliability of a dam(s) constructed as part of the ESP must have a far greater degree of reliability. As a result, the only way to achieve the reliablity level that is required is to perform a comprehensive risk assessment which provides a defensible basis to show that the SG is met.

9. REFERENCES

1. Benjamin, J.R., and C.A. Cornell, Probability, Statistics, and Decision for Civil Engineers, McGraw-Hill Book Company, 1970.

2. Ang, A.H.S, and Tang. W.H., "Probability Concepts in Engineering Planning and Design, Volume I-Basic Principles," John Wiley & Sons, Inc., New York, 1975.

3. U.S. Nuclear Regulatory Commission, "PRA Procedures Guide, A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants, Final Report" Volume 1, NUREG/CR-2300, January 1983.

4. U.S. Department of Energy, Natural Phenomena Hazards Design and Evaluation Guidelines for Department of Energy Facilities, DOE Standard 1020-94, Washington, D.C., April 1994.

5. U.S. Department of Energy, Topical Report YMP/TR-002-NP: Methodology To Assess Fault Displacement and Vibratory Ground Motion Hazards At Yucca Mountain, Office of Civilian Radioactive Waste Management, Las Vegas Nevada, June 1994.

6. U.S. Nuclear Regulatory Commission, "Proposed Revisions To 10 CFR Part 100 and 10 CFR Part 50, and New Appendix S to 10 CFR Part 50," SECY-94-194, Washington, D.C. July 1994.

7. Washington State, "Dam Safety Guidelines Technical Note 2, Selection of Design/Performance Goals For Critical Project Elements," Olympia, Washington, 1993.

8. Nielsen, N.M. and D.N.D. Hartford, Risk Analysis As An Aid To Engineering Judgement In Dam Safety, Proceedings of the Association of State Dam Safety Officials Conference, Boston, Massachusetts, 1994.

9. U.S. Army Corps of Engineers, "Risk-Based Analysis For Evaluation of Hydrology/Hydraulics and Economics in Flood Damage Reduction Studies," Circular No. 1105-2-205, Washington, D.C., February 25, 1994.

10. McCann, M., Jr., and G. A. Hatem, "Development of a Database on Dam Failures and Incidents in the United States," The John A. Blume Earthquake Engineering Center, Stanford University, March 30, 1986.

11. U.S. Atomic Energy Commission, "Reactor Safety Study: An Assessment of Accident Risks in U.S. Nuclear Power Plants," WASH-1400, Washington, D.C.

12. GEI Consultants, Inc., "Chapter 7 - Seismic Hazard Analysis," June 17, 1993.

13. Memorandum From Michael W. West, Michael W. West & Associates, Inc., to Bob Huzjak, GEI Consultants, Inc., dated July 7, 1994.

14. Nuclear Safety Analysis Center, "A Probabilistic Risk Assessment of Oconee Unit 3, Appendix J - Seismic Fragility Curves for Jocassee Dam and Oconee Dikes," NSAC/60, Electric Power Research Institute, Palo Alto, California, 1984.

15. Sewell, R.T., and McGuire, R.K., "Determination of Review Level Earthquakes for Evaluation of Nuclear Power Plant Resistances to Potential Severe Seismic Accidents," Electric Power Research Institute, Palo Alto, California, Draft Report, September, 1989.

16. Sewell, R.T., "Simplified Seismic Reliability analysis of Earth Dams," Stanford University, John A. Blume Earthquake Engineering Center, Technical Report No. 66, July 1984.

17. GEI Consultants, Inc., "Emergency Storage Project, Phase 1 Engineering Study, Technical Memorandum No. 2, Seismotectonic Hazard Evaluation of Alternative Dam and Reservoir Sites," prepared for San Diego County Water Authority, Carlsbad, California, March 1994.

18. Yegian, M.K, E.A. Marciano, and V.G. Ghahraman, "Integrated Seismic Risk Analysis for Earth Dams," Northeastern University, Report No. CE-88-15, December 1988.

19. ASCE Task Committee on Spillway Design Flood Selection, "Evaluation Procedures for Hydrologic Safety of Dams," ASCE, New York, 1988.